

# Today The Sun

## Events

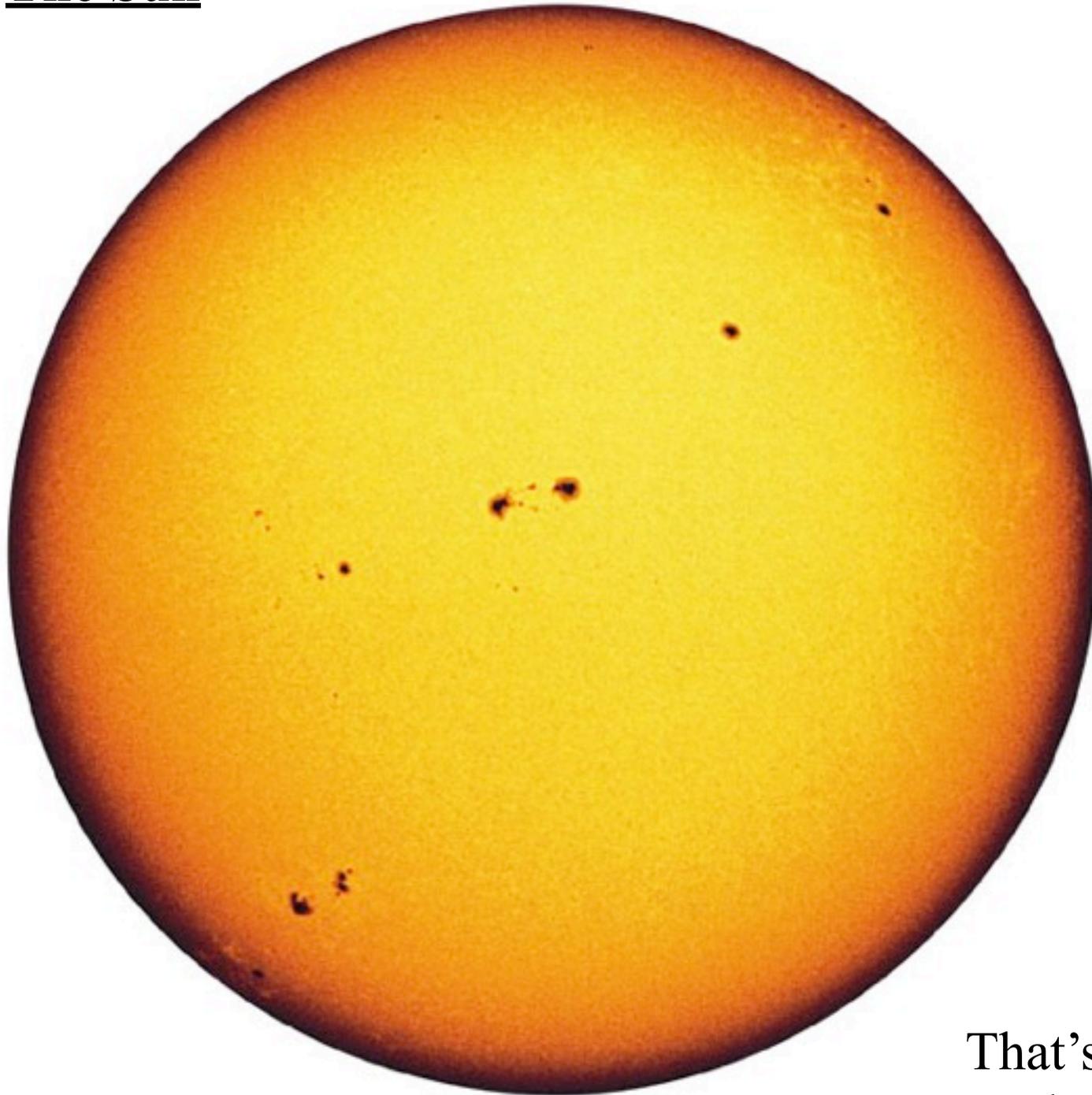
Homework due next time (last class)  
- will count best 5 of 6

Final exam Dec. 15 @ 12:30 here

# The Sun

- the main show in the solar system
  - 99.8% of the mass
  - 99.9999...% of the energy

# The Sun



## ***Radius:***

$$6.9 \times 10^8 \text{ m}$$

(109 times Earth)

## ***Mass:***

$$2 \times 10^{30} \text{ kg}$$

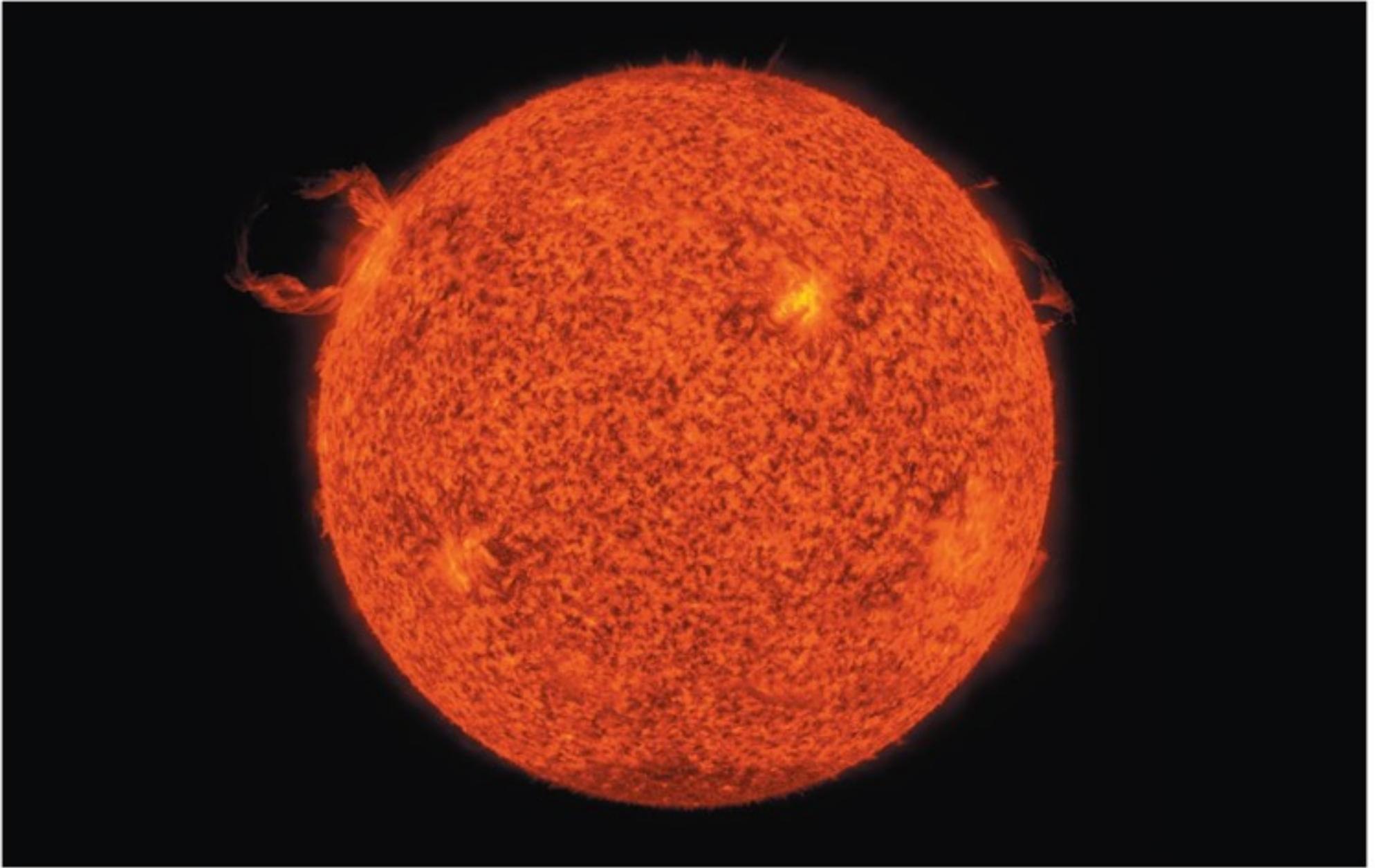
(1,000 Jupiters;  
300,000 Earths)

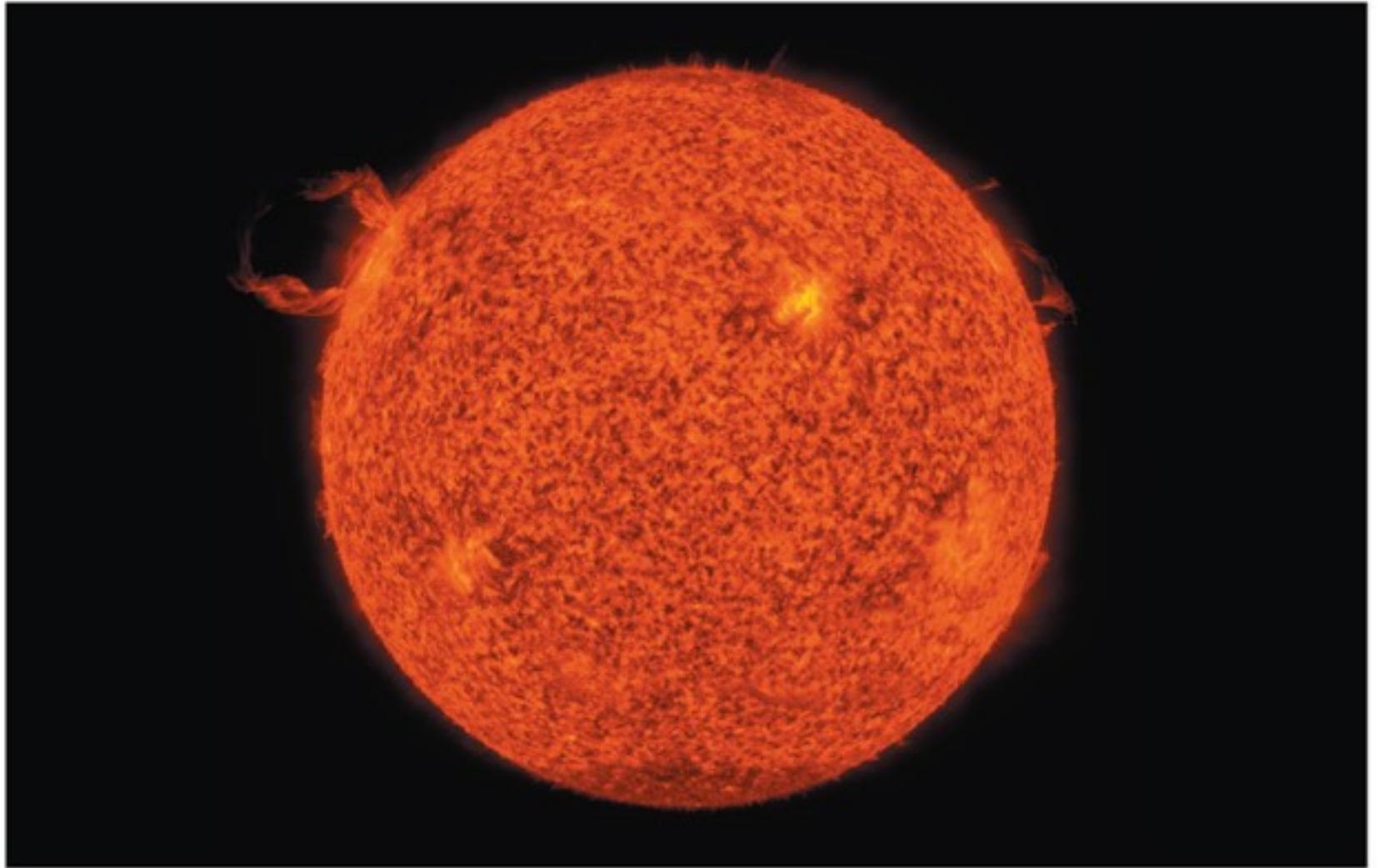
## ***Luminosity:***

$$3.8 \times 10^{26} \text{ watts}$$

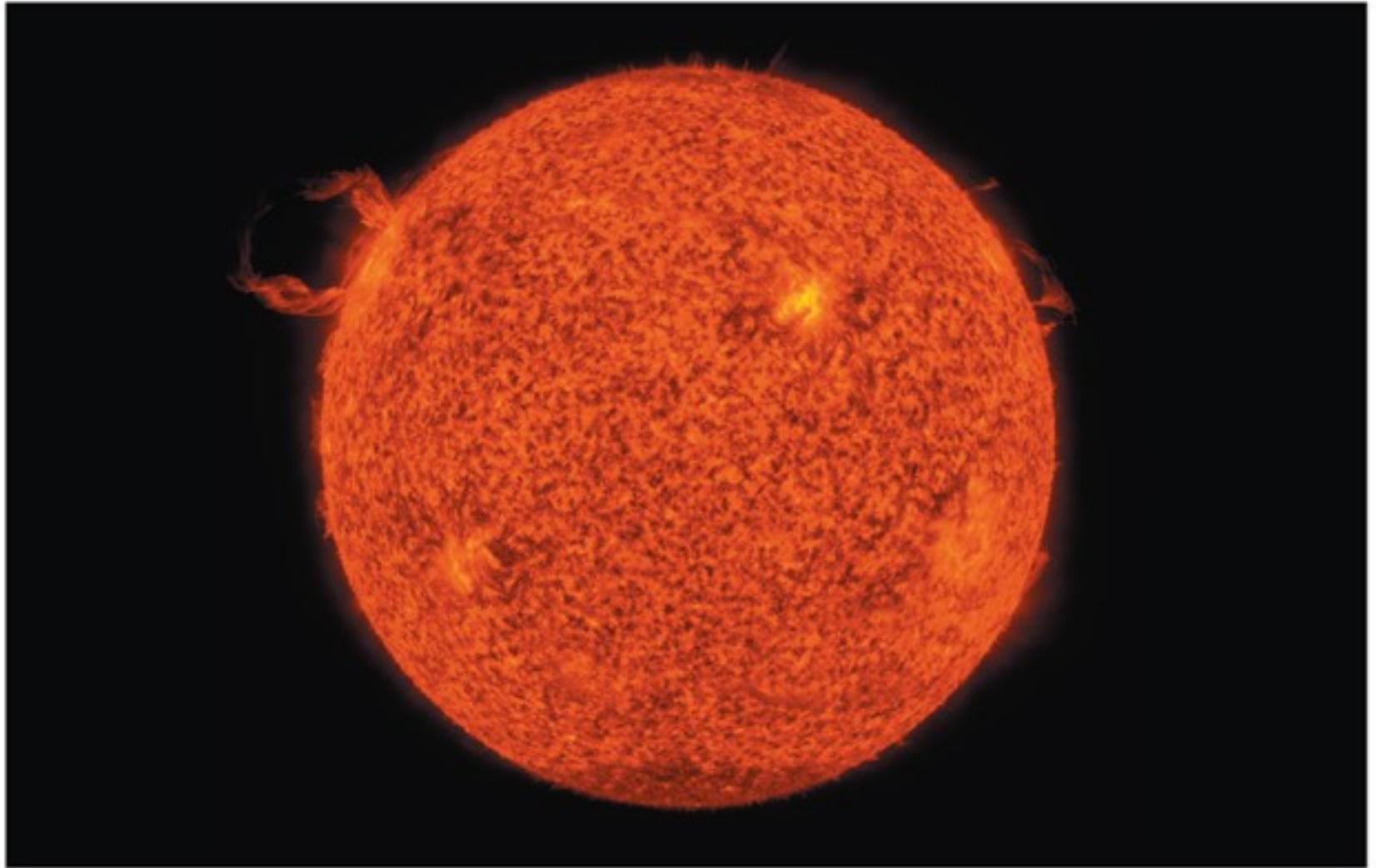
That's about a billion big  
nuclear bombs every second

# Why does the Sun shine?



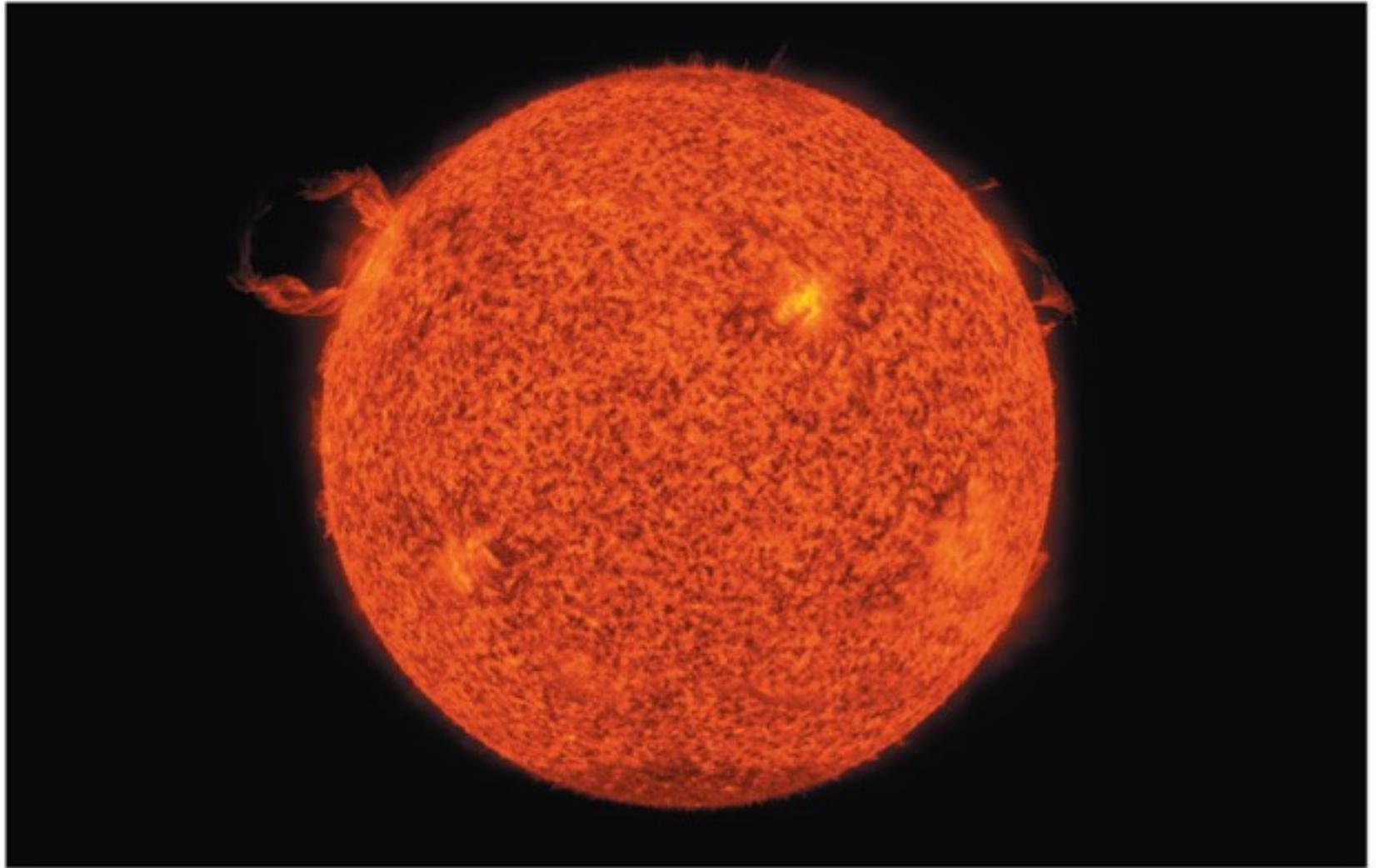


***Is it on FIRE?***



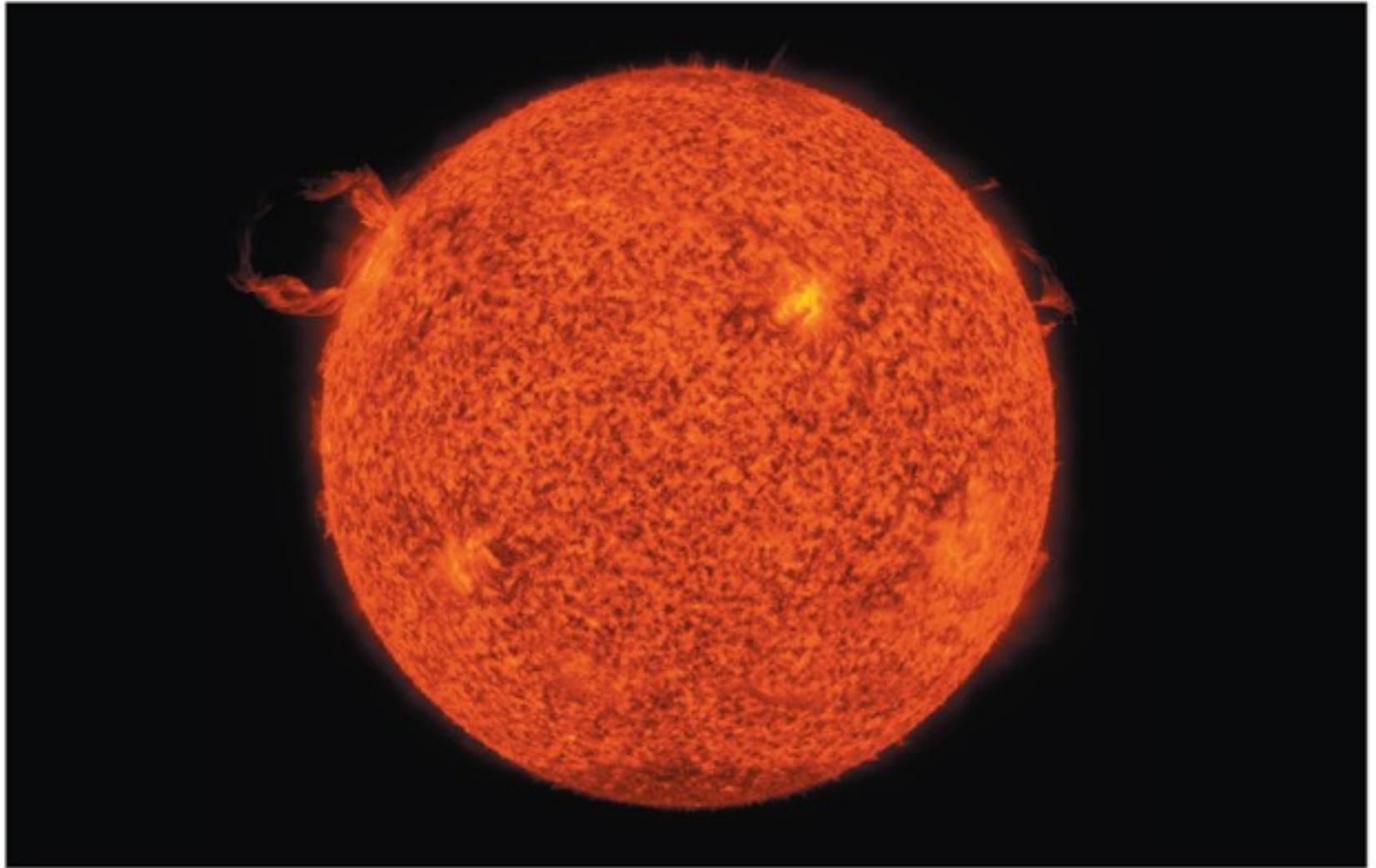
***Is it on FIRE?***

$$\frac{\text{Chemical energy content}}{\text{Luminosity}} \sim 10,000 \text{ years}$$

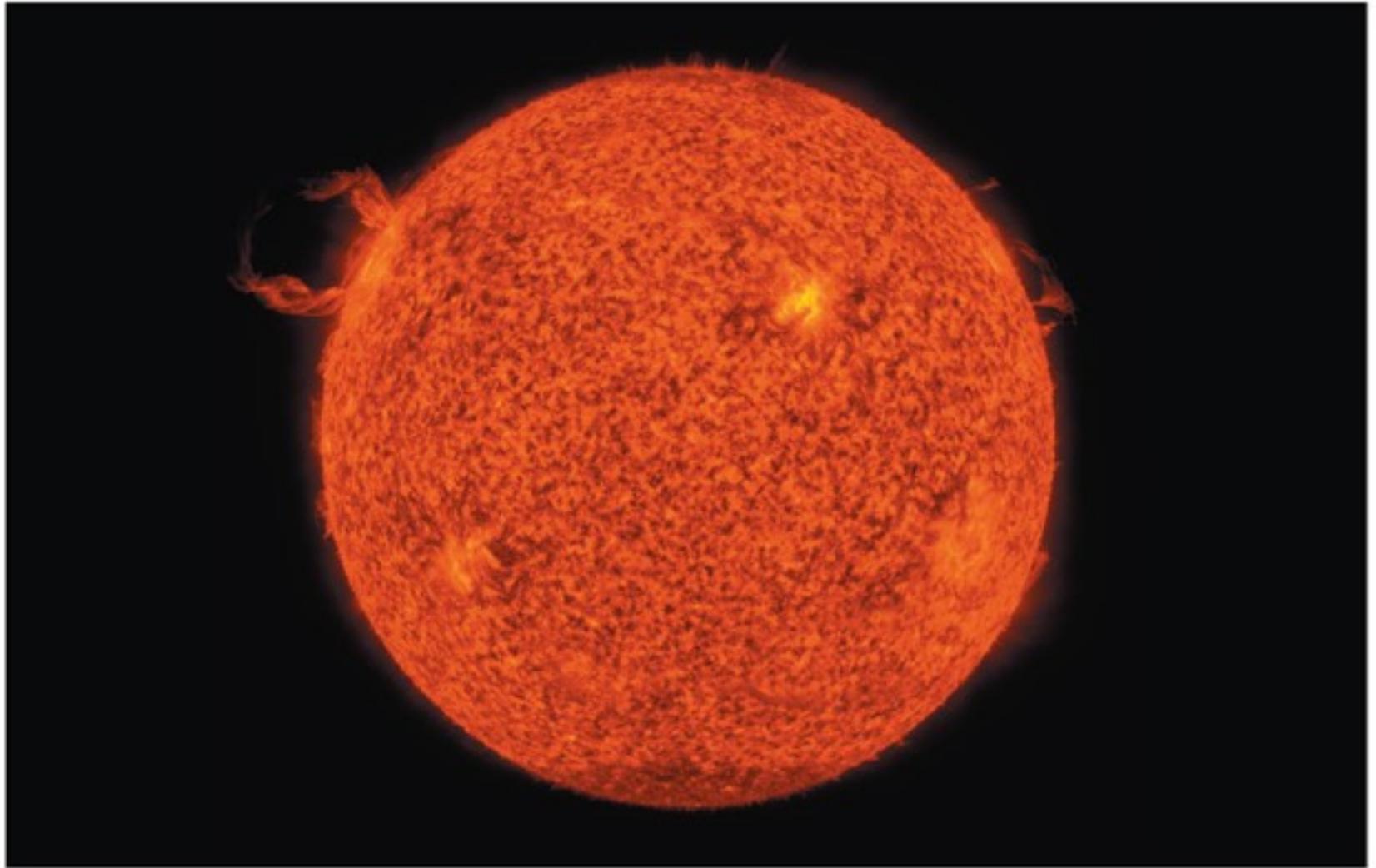


***Is it on FIRE? ... NO!***

Energy Available  $\triangleright$  Chemical energy content  $\sim$  10,000 years  
Rate of Energy Use  $\triangleright$   $\frac{\text{Chemical energy content}}{\text{Luminosity}}$

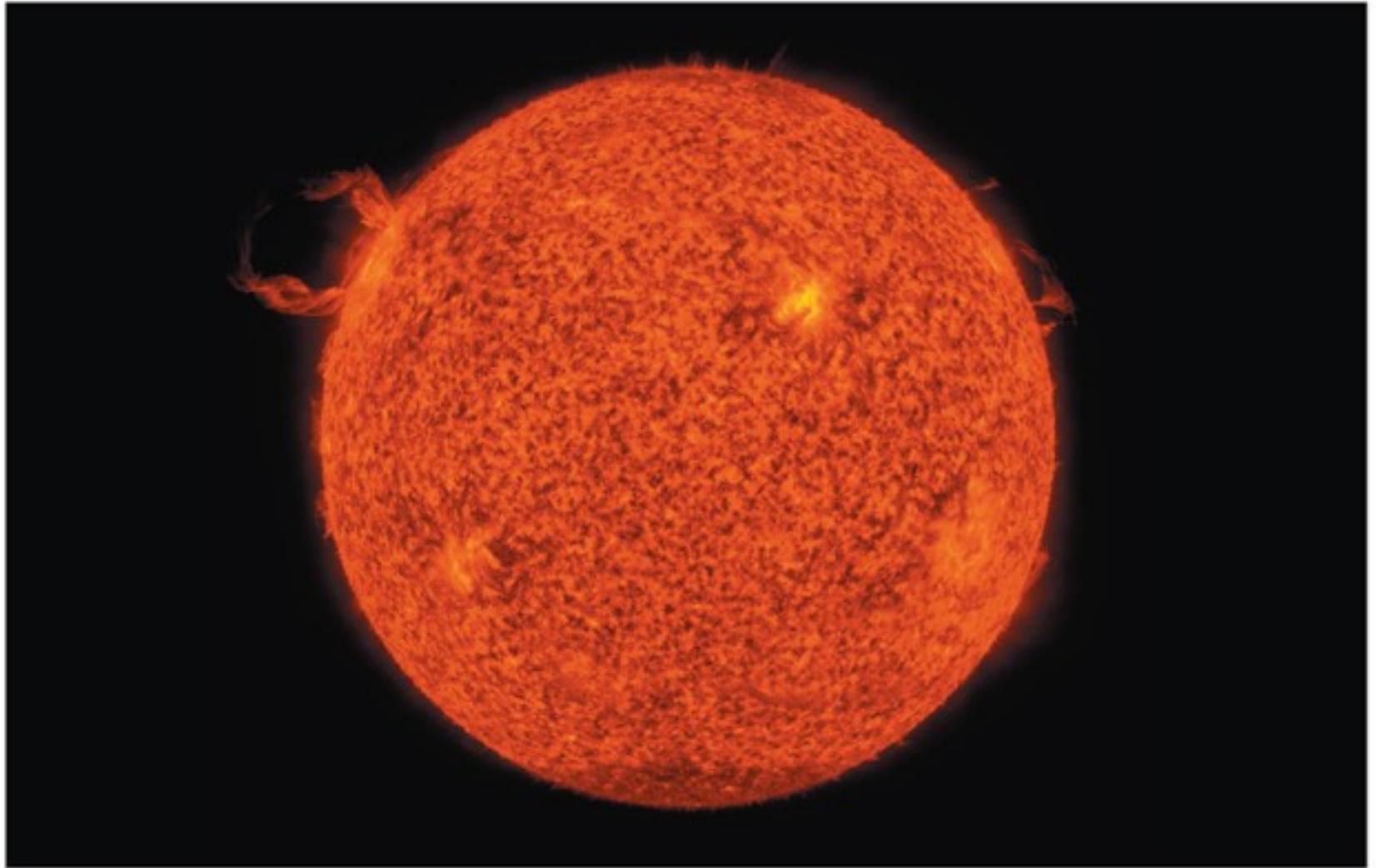


***Is it CONTRACTING?***



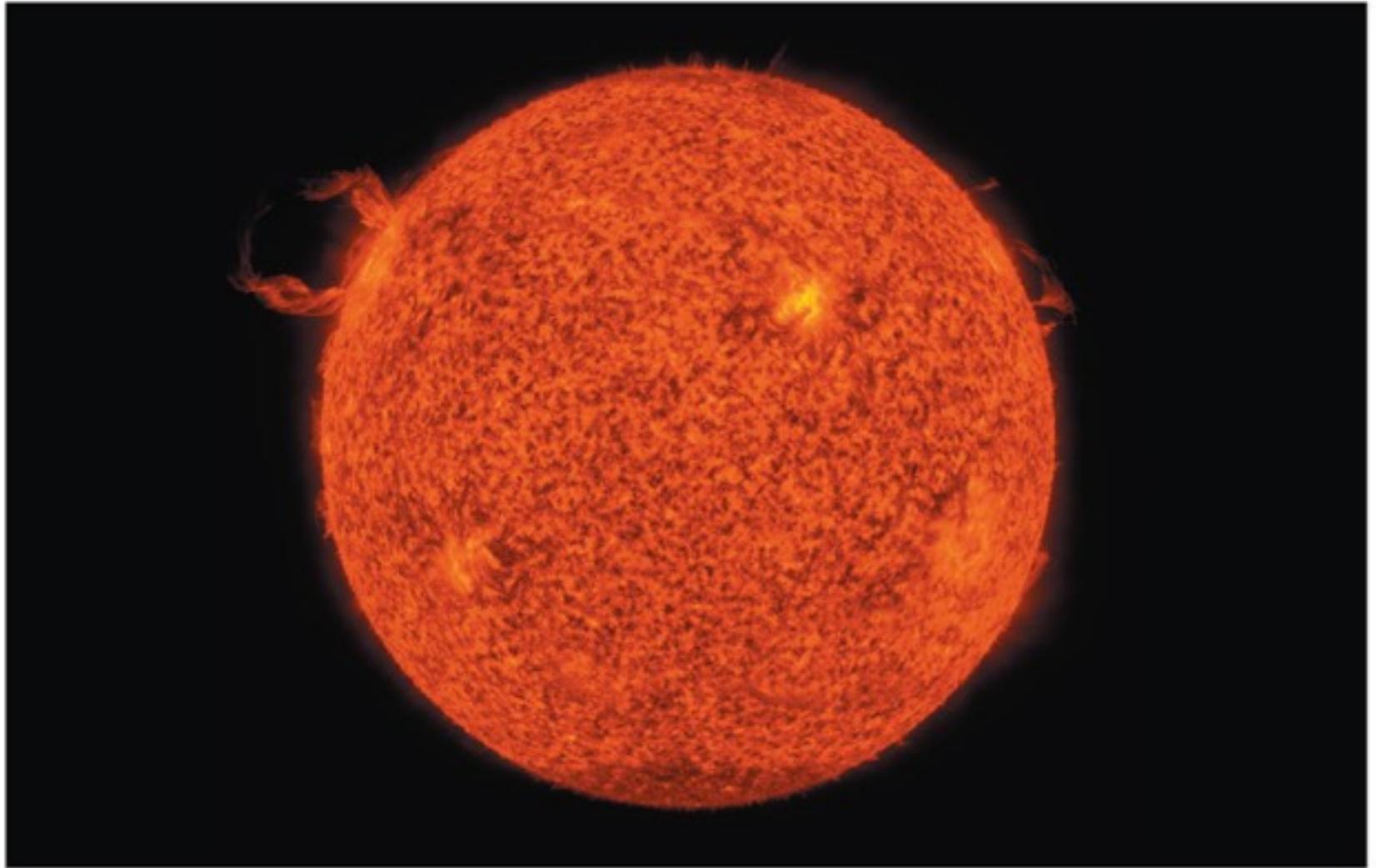
***Is it CONTRACTING?***

$$\frac{\text{Gravitational potential energy}}{\text{Luminosity}} \sim 25 \text{ million years}$$



***Is it CONTRACTING? ... NO!***

$$\frac{\text{Gravitational potential energy}}{\text{Luminosity}} \sim 25 \text{ million years}$$



***It can be powered by NUCLEAR ENERGY! ( $E = mc^2$ )***

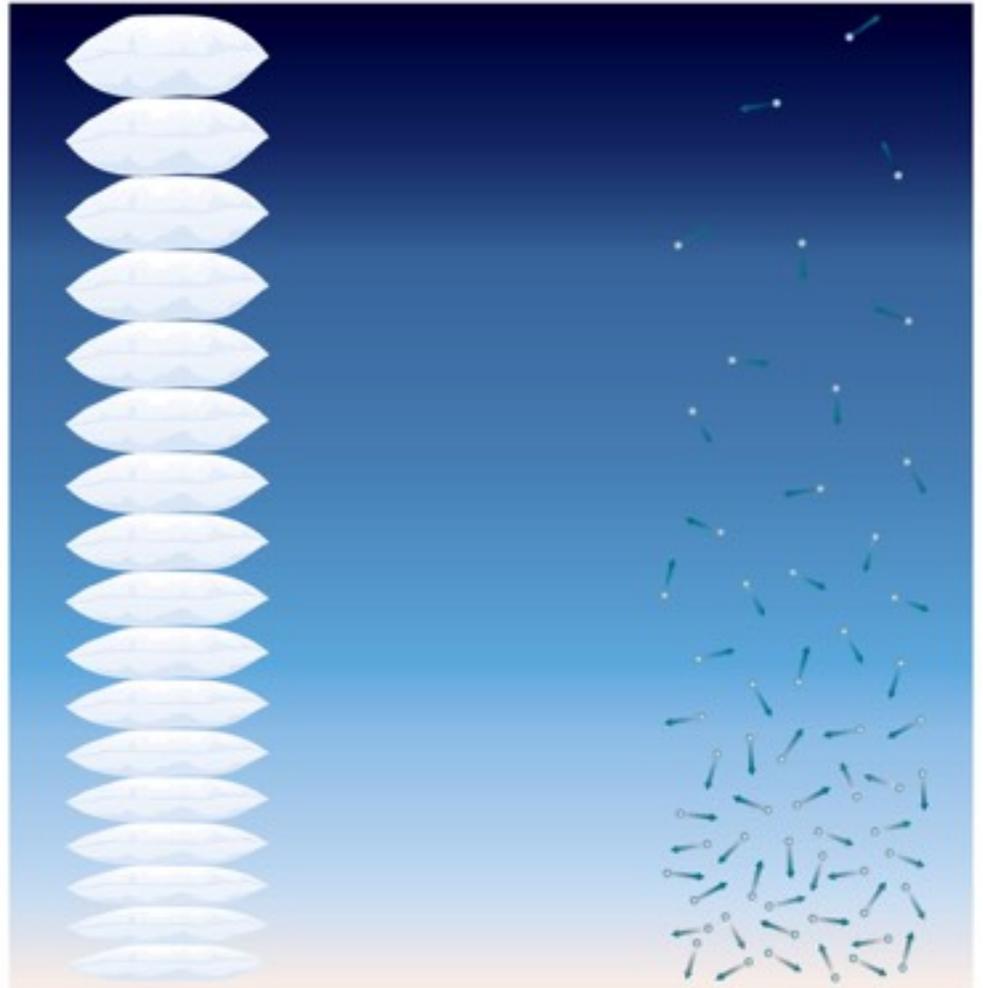
Nuclear potential energy (core) with 0.7% efficiency

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Luminosity ~ 10 billion years

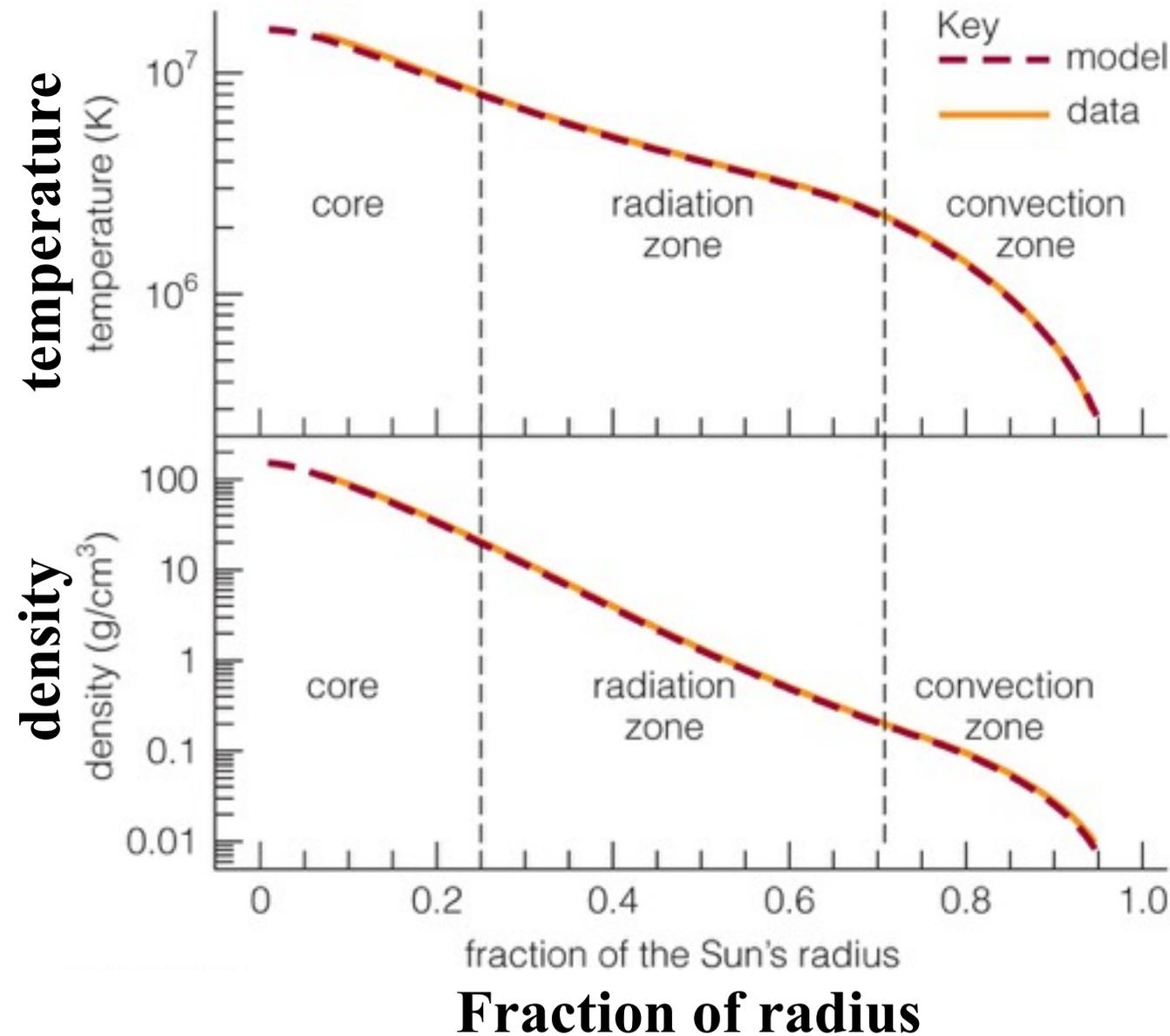
- **Why the Sun shines**

- Chemical and gravitational energy sources could not explain how the Sun could sustain its luminosity for more than about 25 million years.
- The Sun shines because **gravitational equilibrium** keeps its core hot and dense enough to release energy through nuclear fusion.
  - Hydrogen fuses into Helium in a 3-step process called the proton-proton chain.



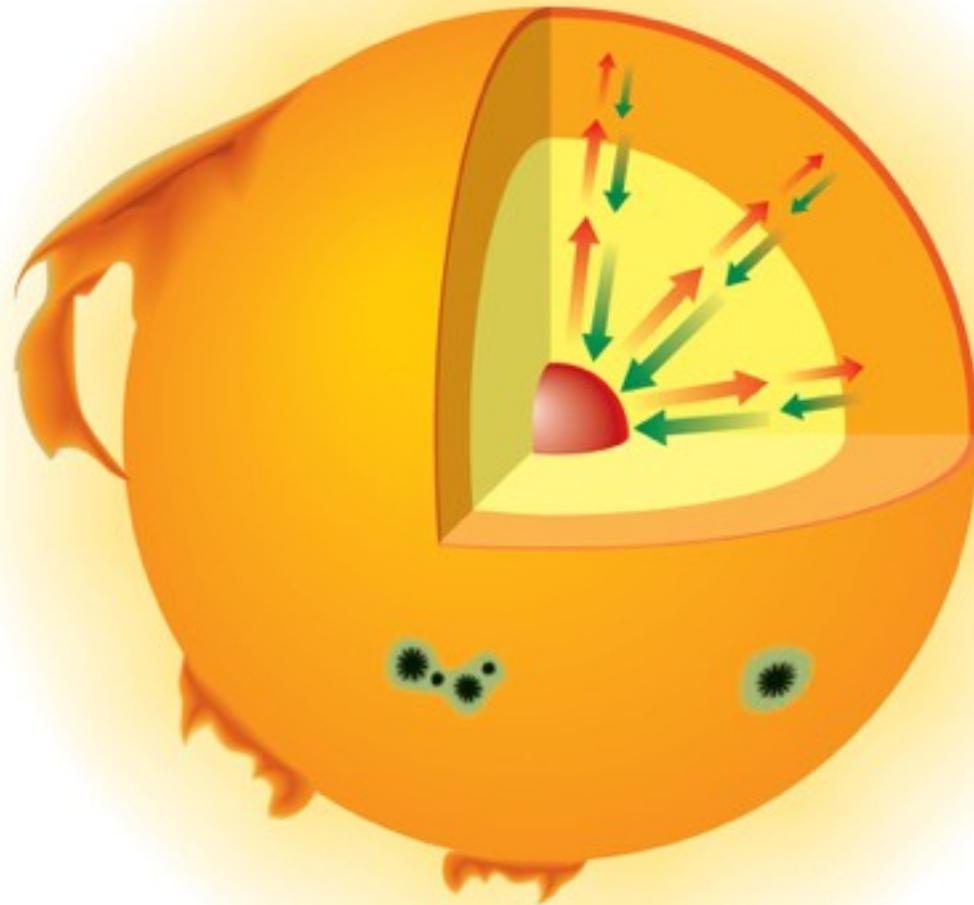
- Weight of upper layers compresses lower layers.

# Interior Structure of the Sun



- Gravity causes the density and temperature to increase towards the center.
- Ave. density about 1 g/cc (water)
- but
  - much denser in core
  - much thinner at surface

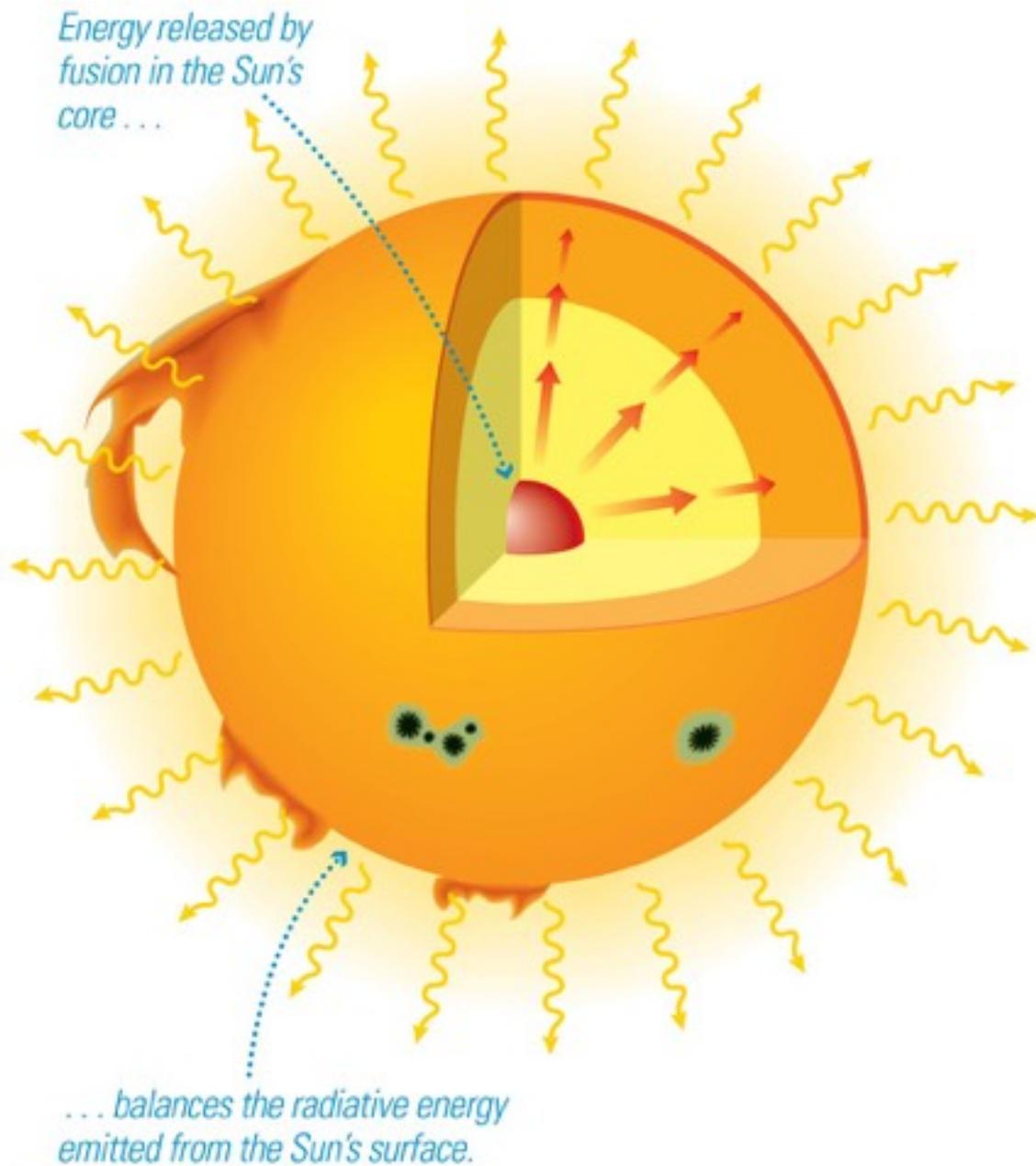
pressure →  
gravity ←



Stars are stable:  
pressure balances  
gravity.

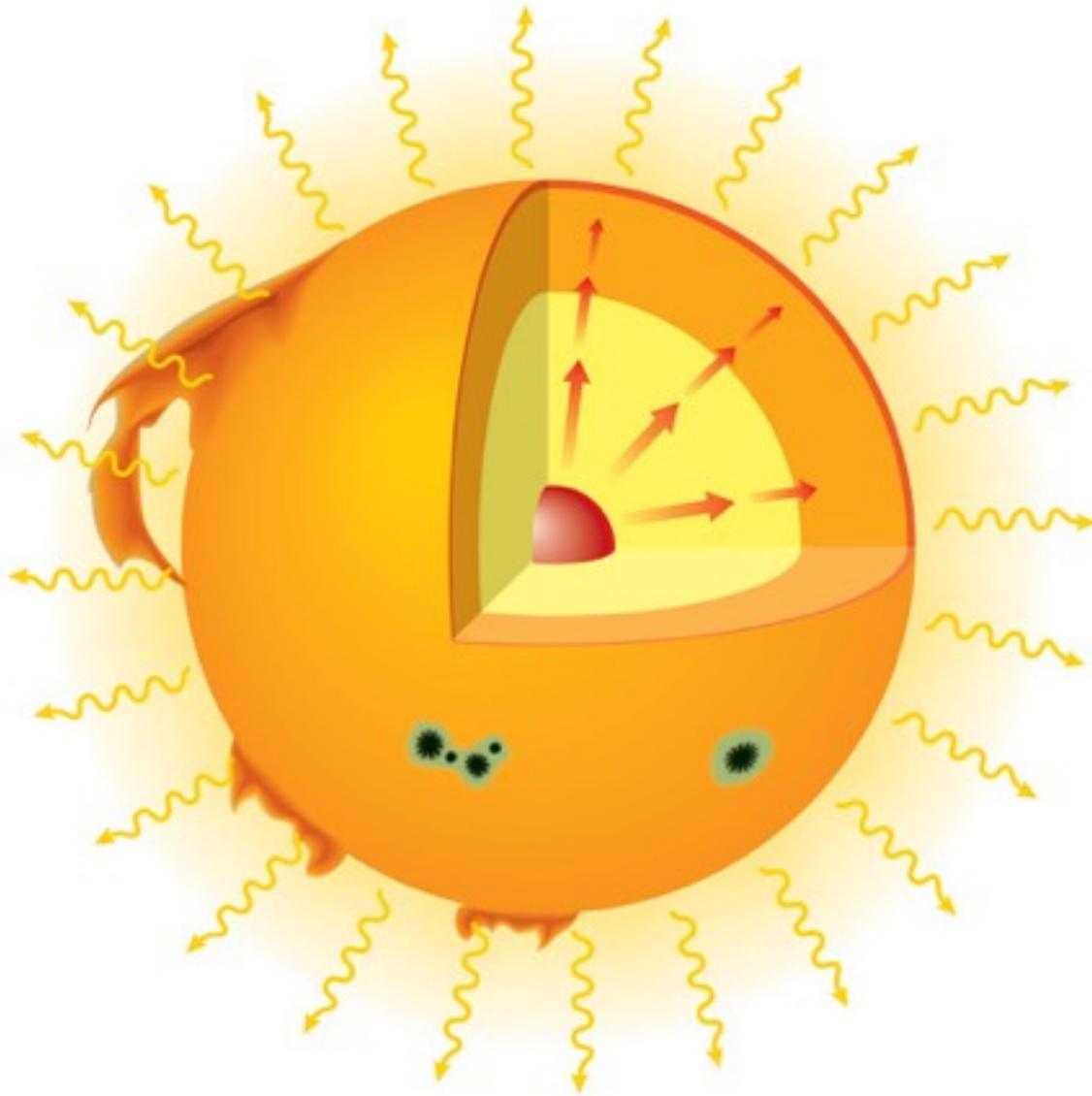
*Hydrostatic  
equilibrium:*

Energy released  
by nuclear fusion  
in the core of the  
sun heats the  
surrounding gas.  
The resultant  
pressure balances  
the relentless  
crush of gravity.



## ***Energy Balance:***

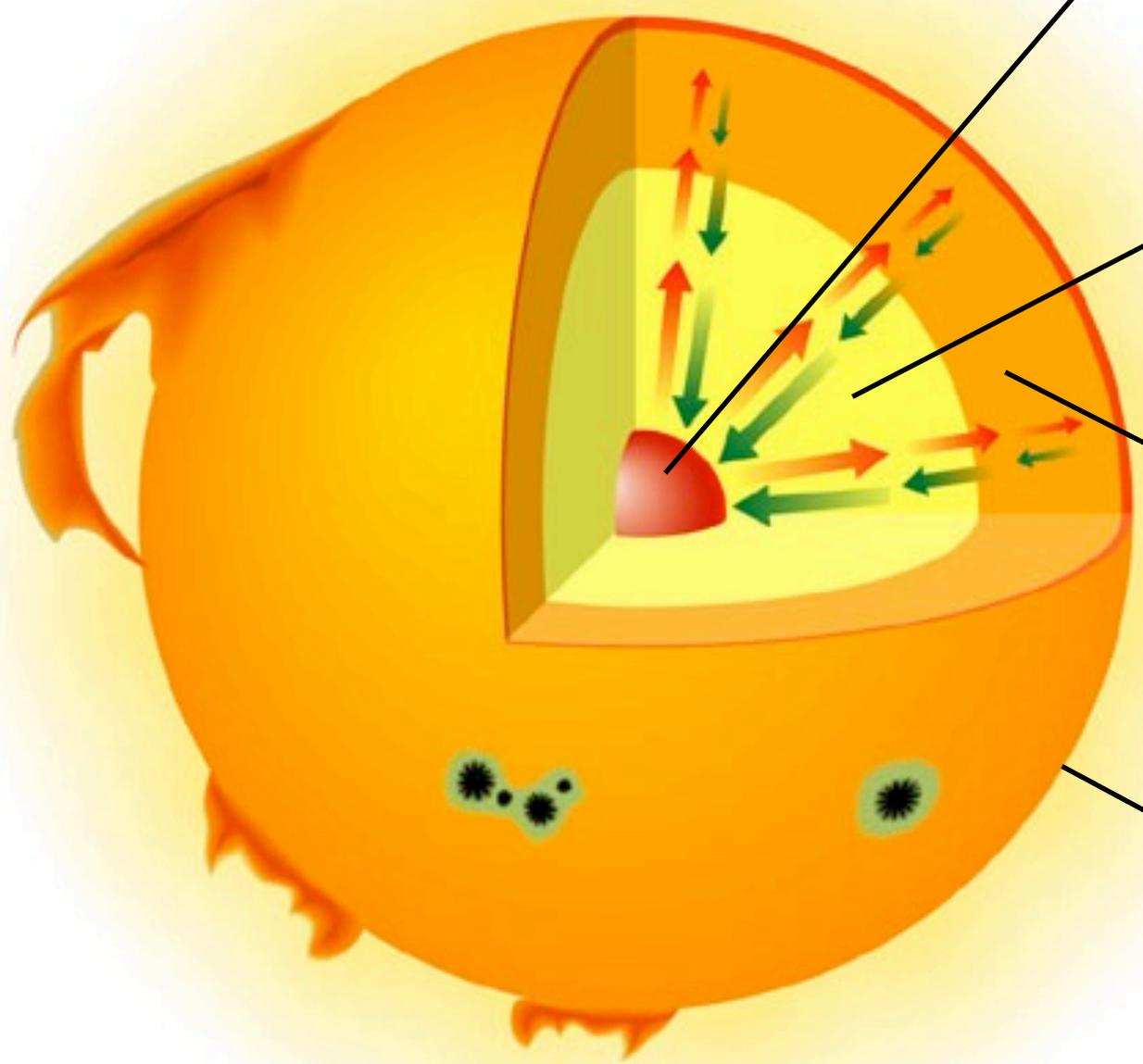
- The rate at which energy radiates from the surface of the Sun must be the same as the rate at which it is released by fusion in the core.



***initial  
gravitational  
contraction:***

- Provided the energy that heated the core as Sun was forming
- Contraction stopped when fusion began.

pressure →  
gravity ←



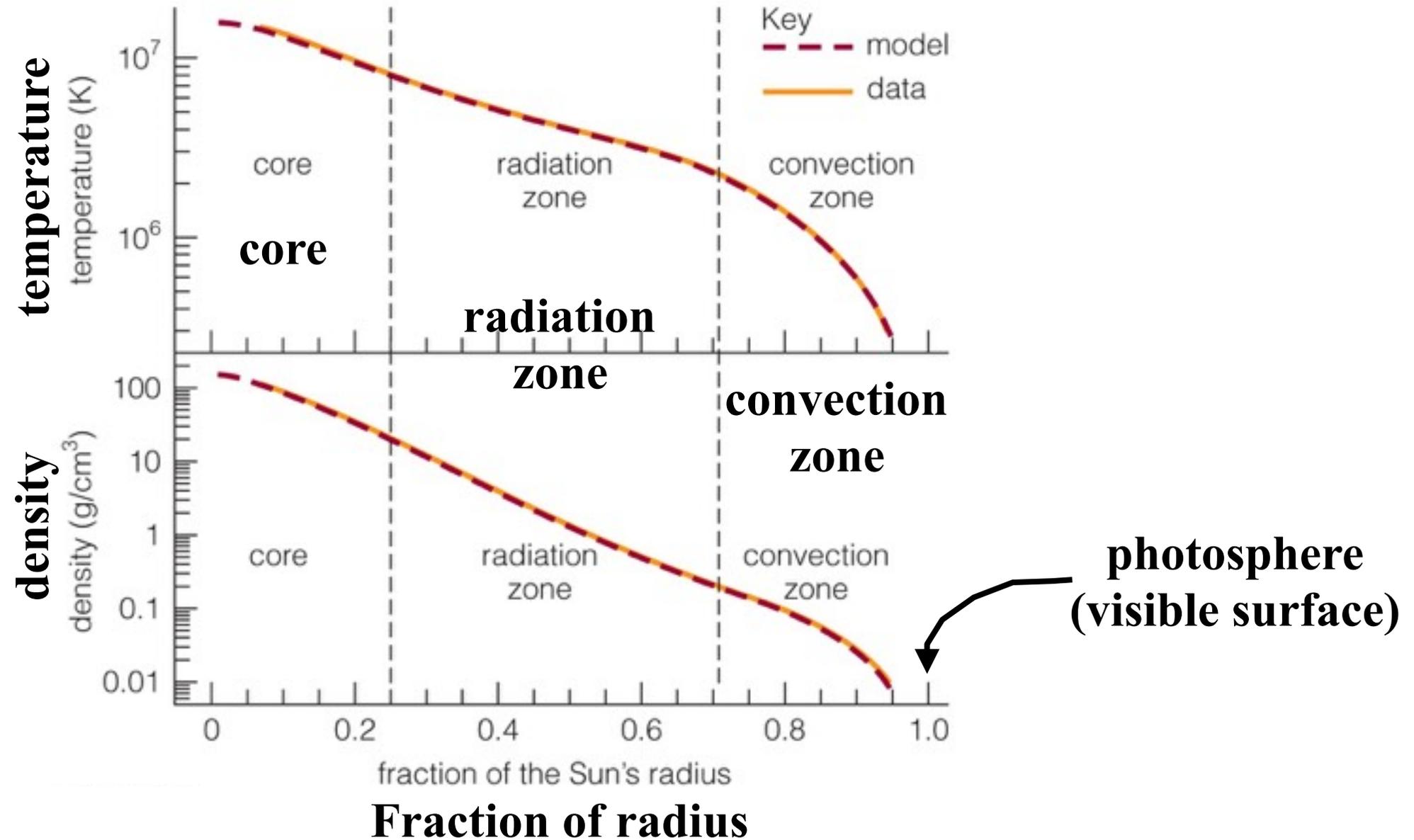
**Core:**  
Energy generated  
by nuclear fusion  
~ 15 million K

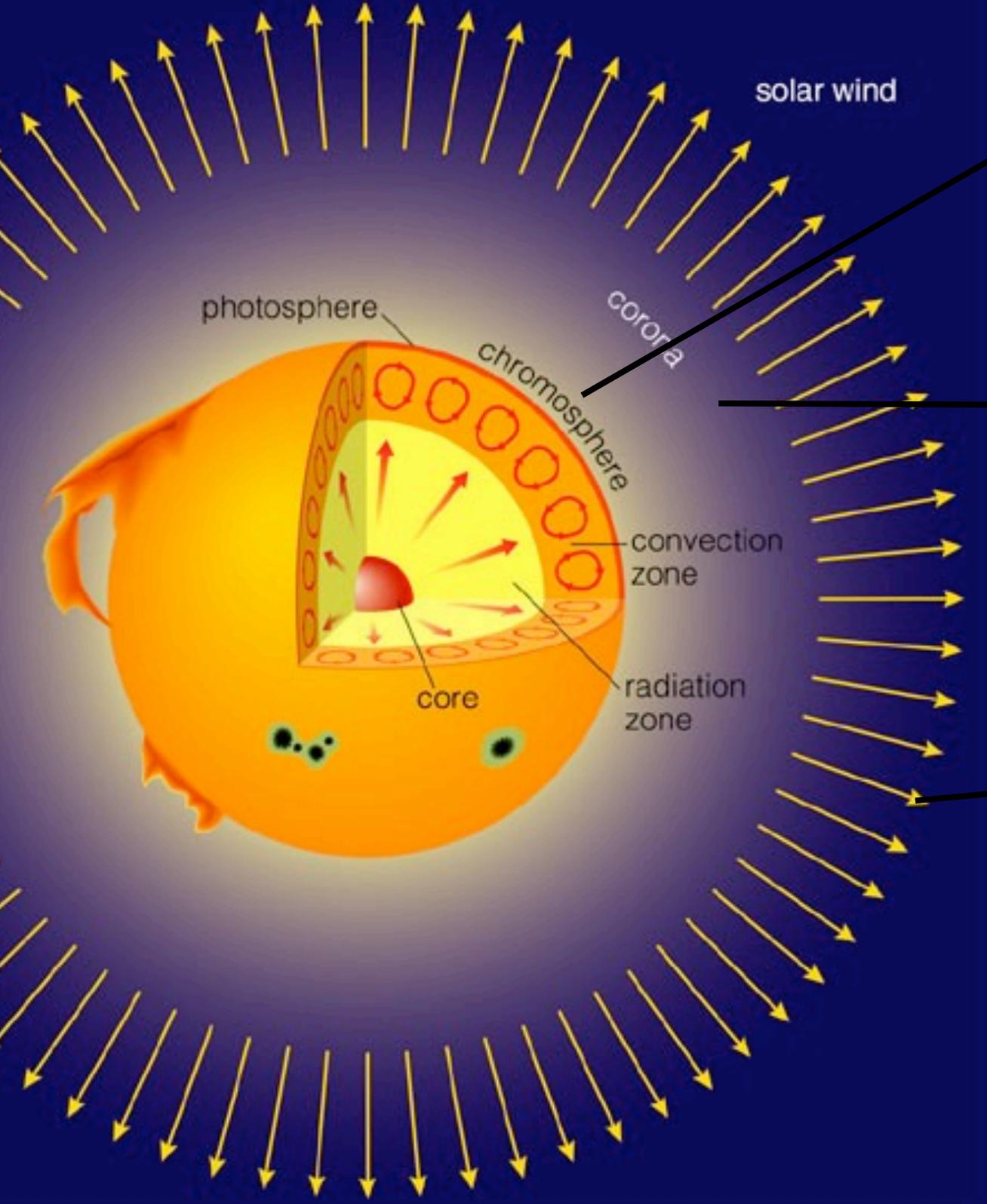
**Radiation zone:**  
Energy transported  
upward by photons

**Convection zone:**  
Energy transported  
upward by rising  
hot gas

**Photosphere:**  
Visible surface  
~5,800 K

# Interior Structure of the Sun





***Chromosphere:***  
Middle layer of solar atmosphere

***Corona:***  
Outermost layer of solar atmosphere

***Solar wind:***  
A flow of charged particles from the surface of the Sun

Little mass in these components

- **Solar structure**

- From inside out, the layers are:

- Core

- Energy generation by fusion reactions

- Radiation zone

- Outward energy transport by photons

- Convection zone

- Outward energy transport by gas motions

- Photosphere

- Luminous surface (energy emitted to space)

- » absorption spectrum

- Chromosphere

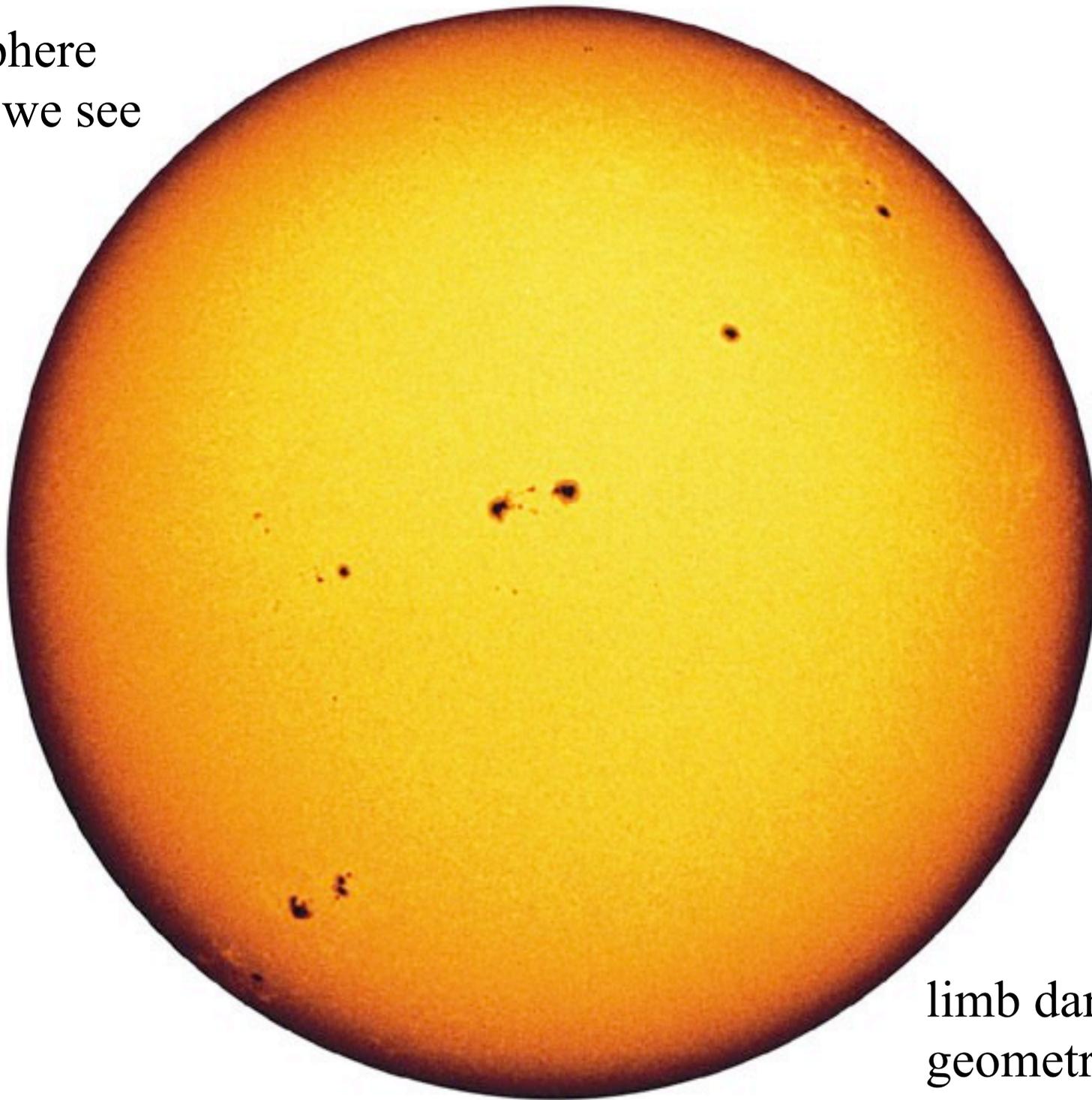
- low density upper atmosphere

- » emission spectrum, but much fainter than photosphere

- Corona

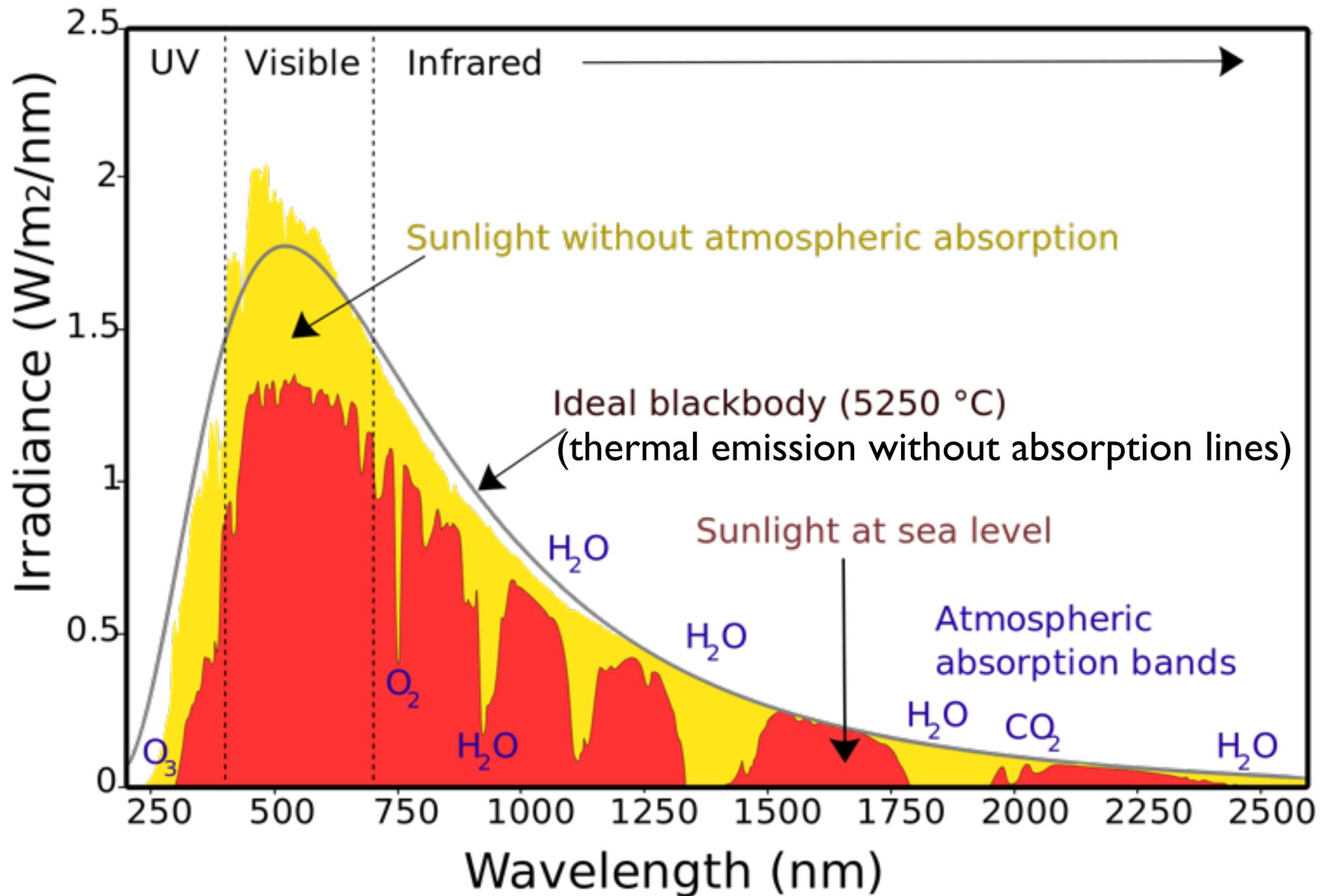
- very hot, low density plasma tailing off into space

Photosphere  
is what we see

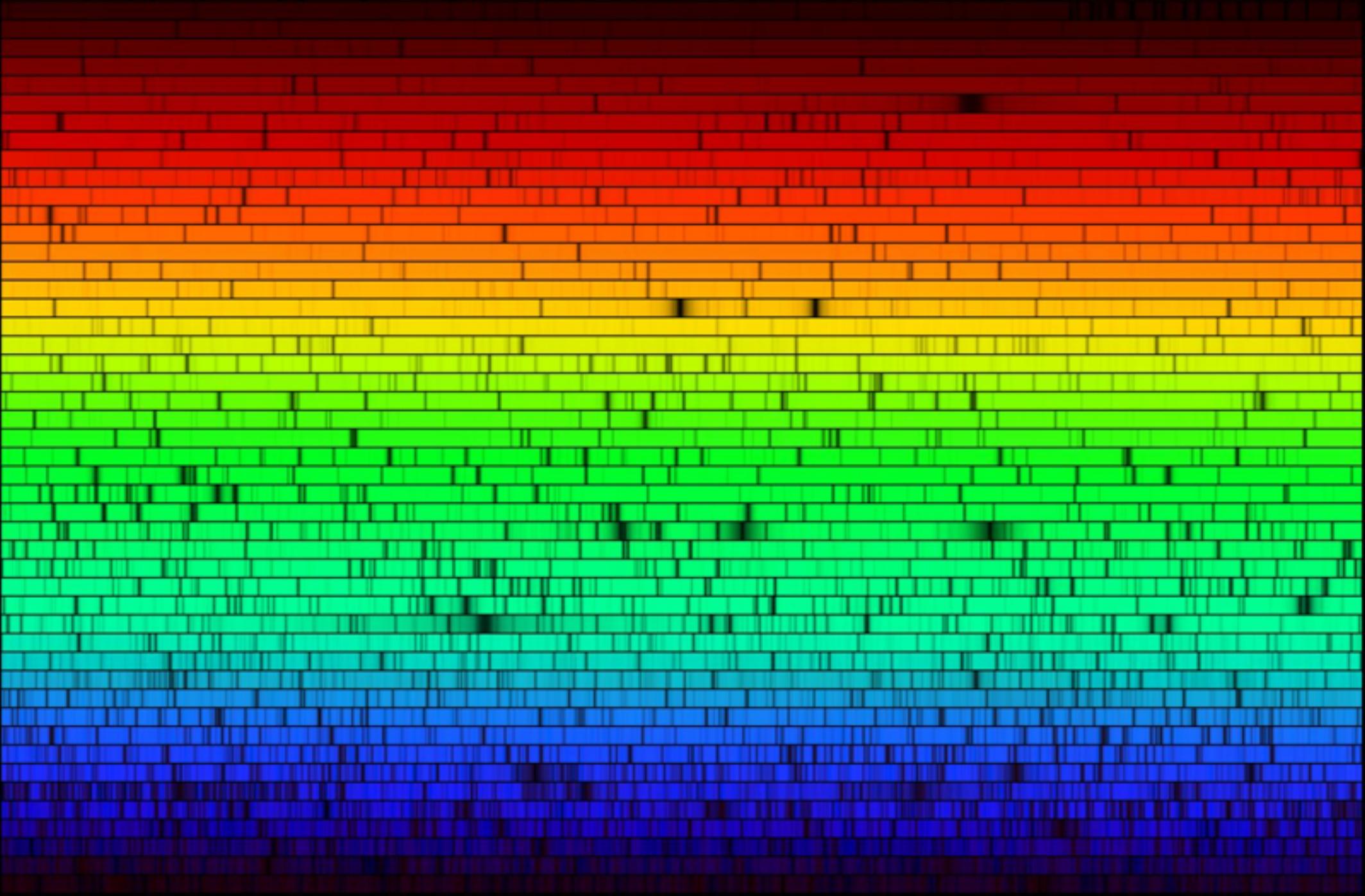


limb darkening is a  
geometric effect

# Spectrum of Solar Radiation (Earth)

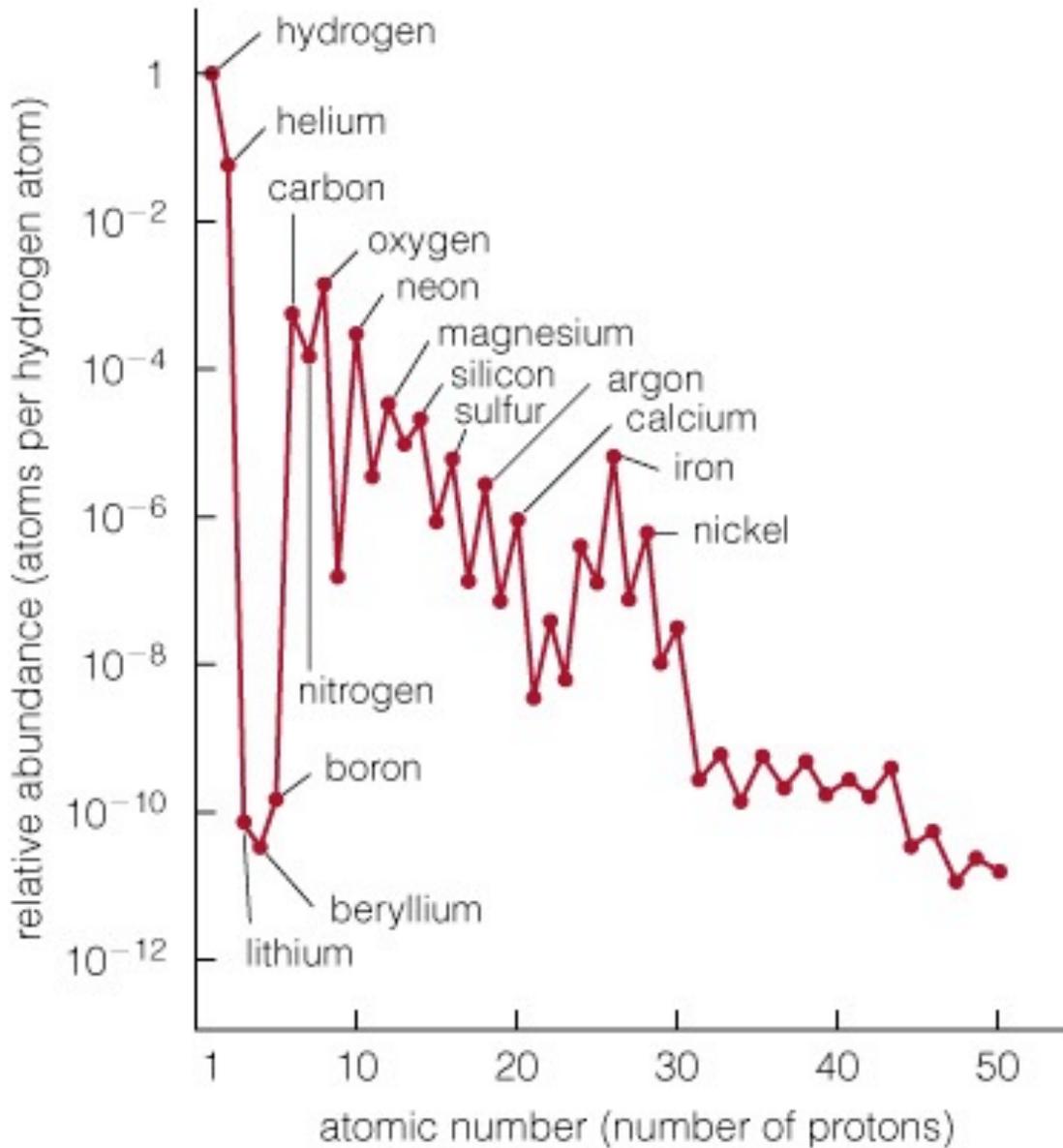


The photosphere produces an absorption spectrum



# Composition determined from absorption lines

Abundance (by number relative to Hydrogen)



Atomic number (number of protons)

By mass, the sun is  
3/4 Hydrogen  
1/4 Helium  
< 2% everything else

This is typical of the universe; Earth is an exception.

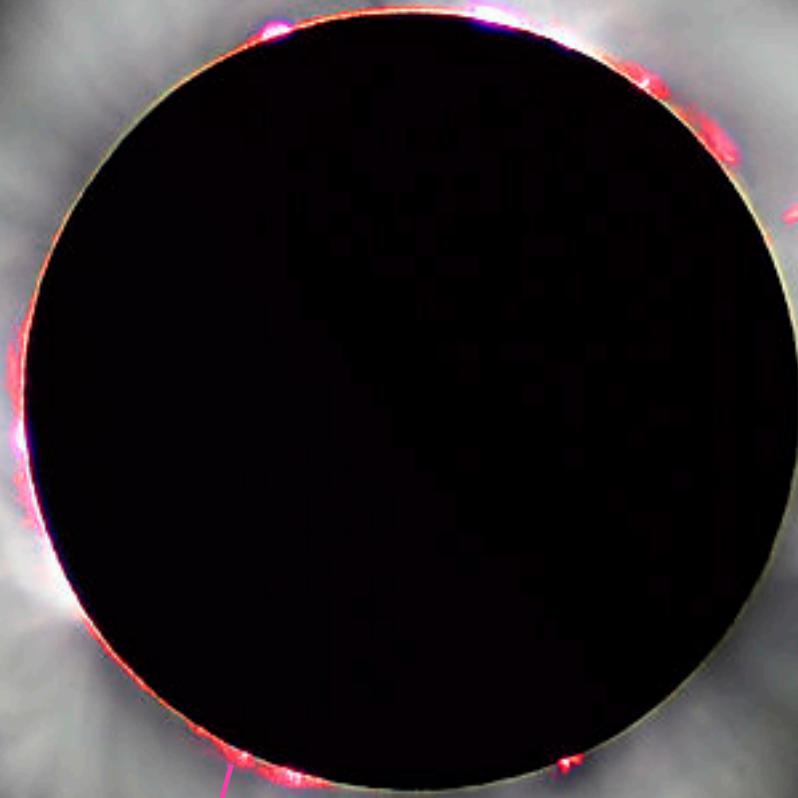
Helium *discovered* in the spectrum of the sun (hence the name)

solar corona

only visible during  
eclipse - greatly  
outshone by  
photosphere  
normally

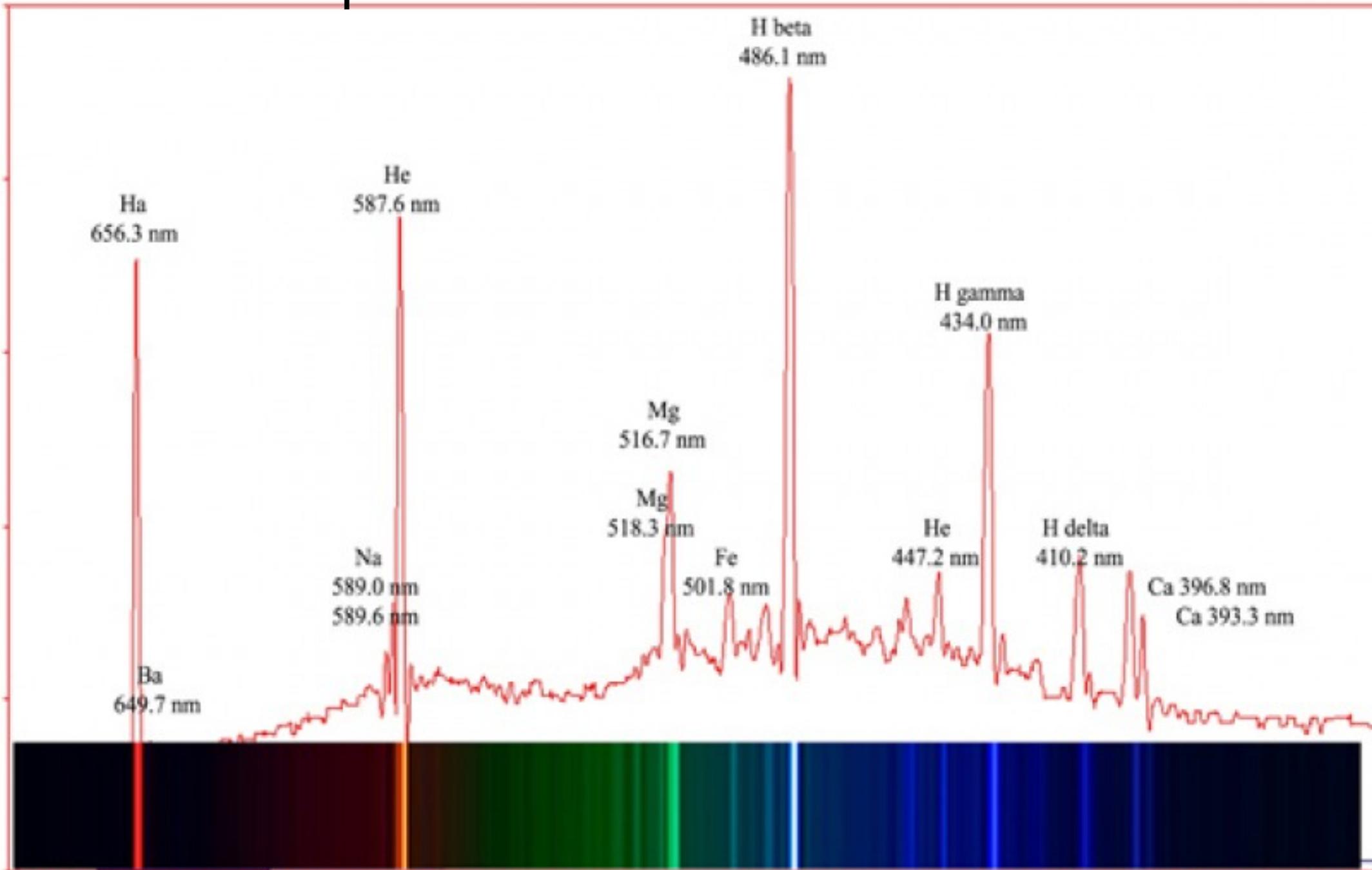
solar chromosphere

seen in  $H\alpha$  emission

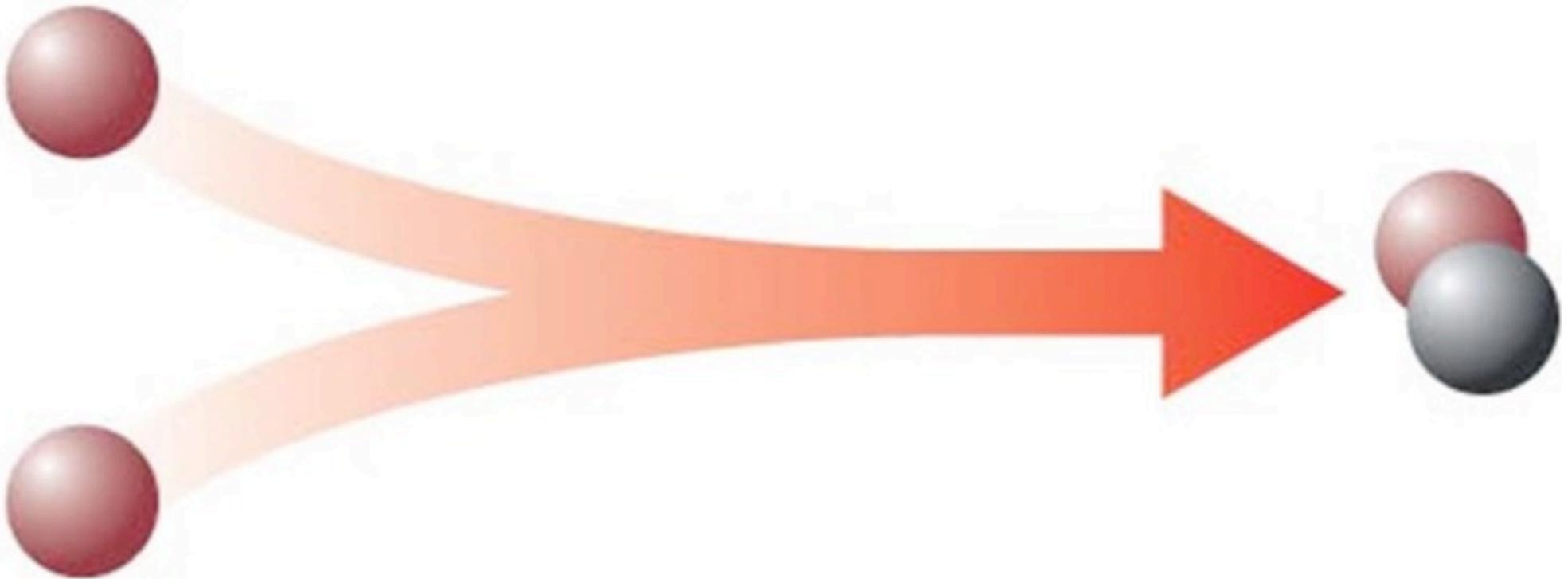


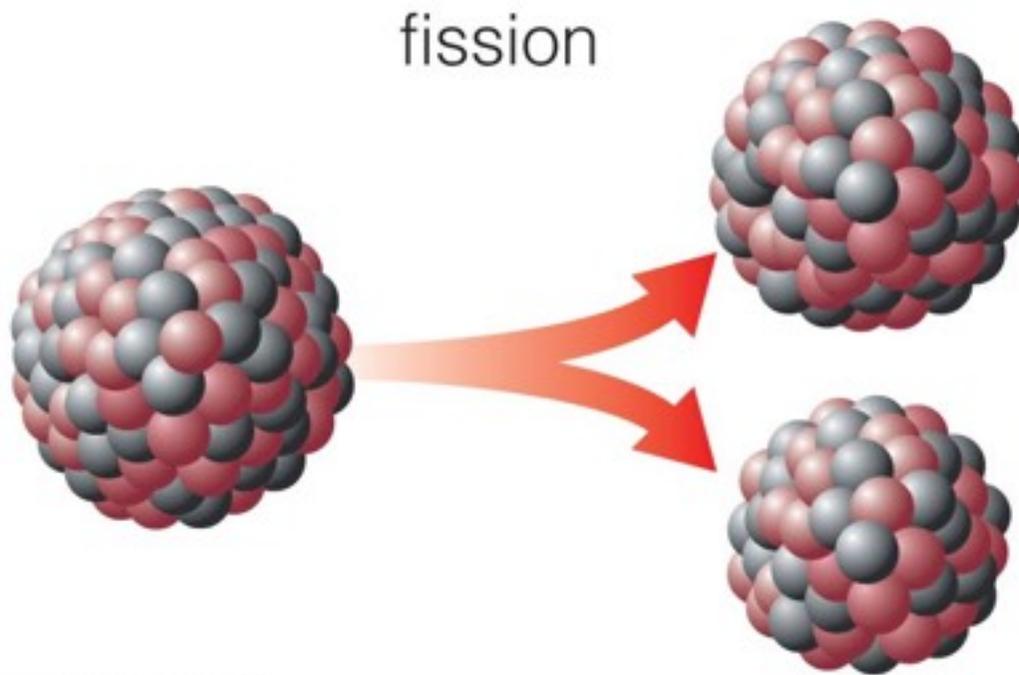
# The Solar Chromosphere Spectrum (Flash Spectrum)

emission line spectrum



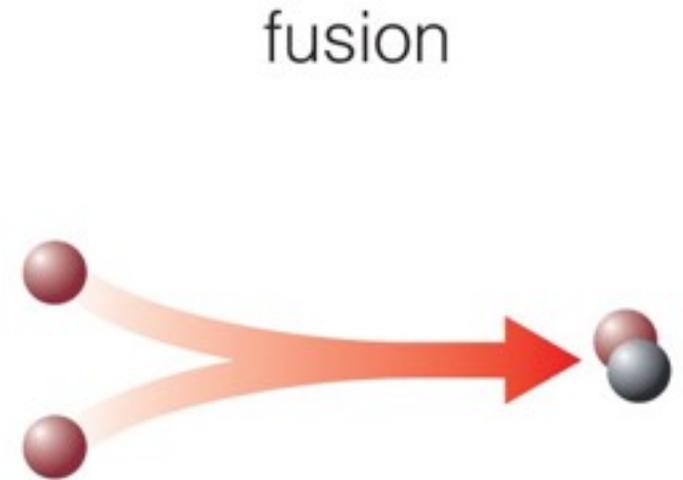
# Nuclear fusion powers the Sun





## ***Fission***

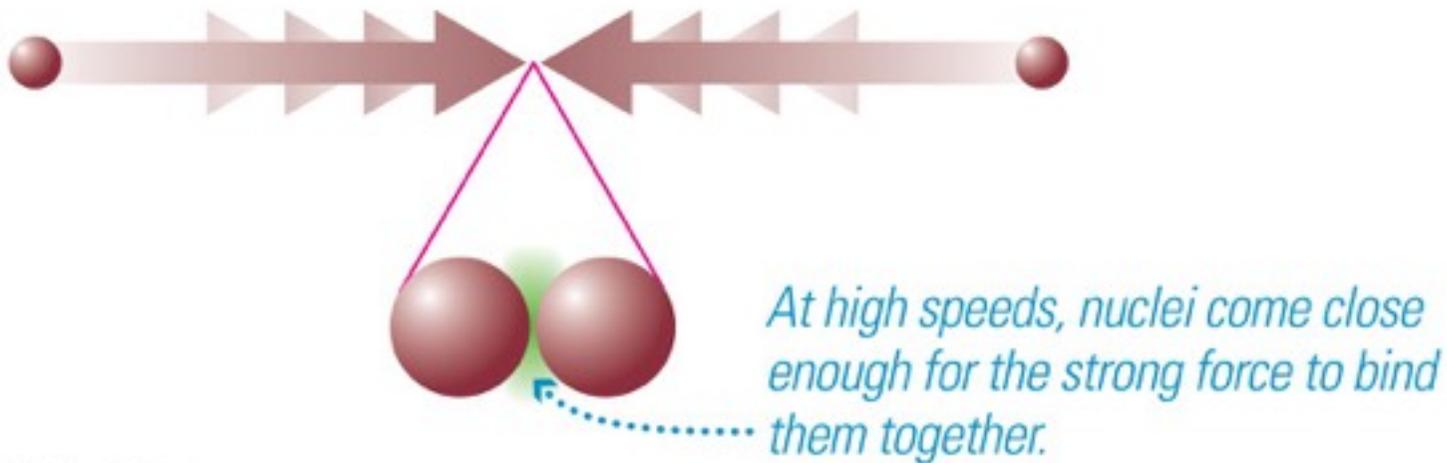
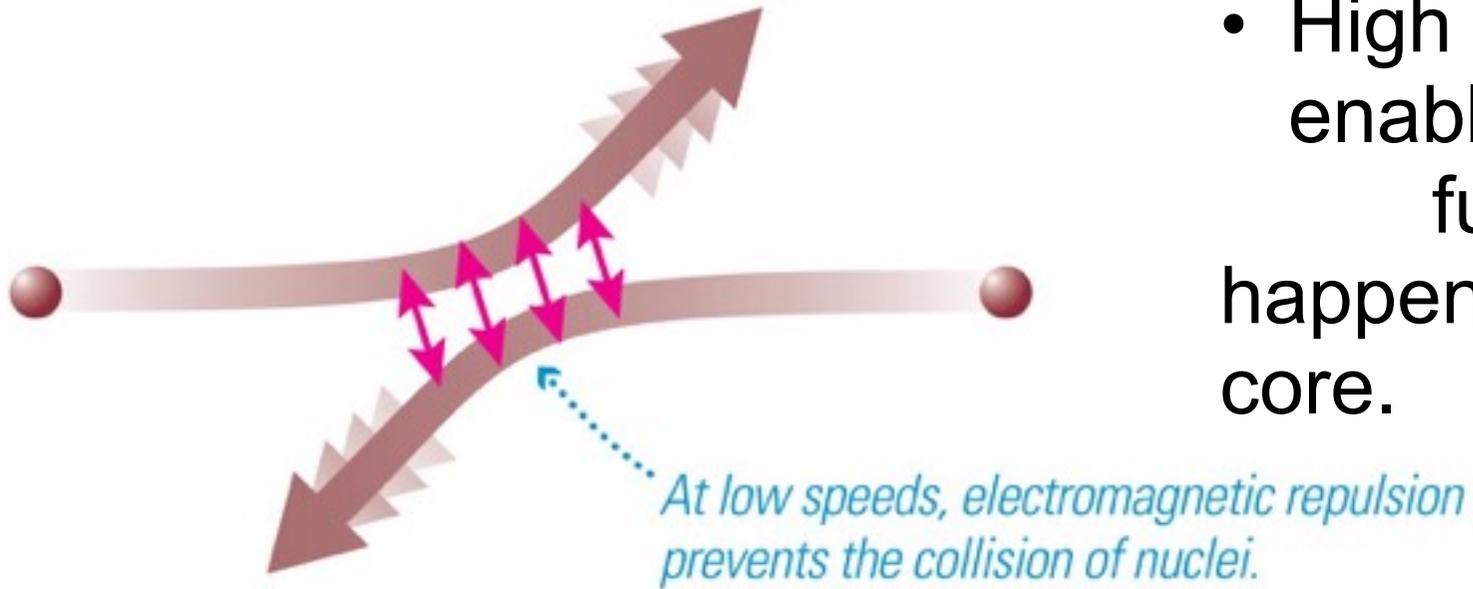
- Big nucleus splits into smaller pieces.
- (Example: nuclear power plants)

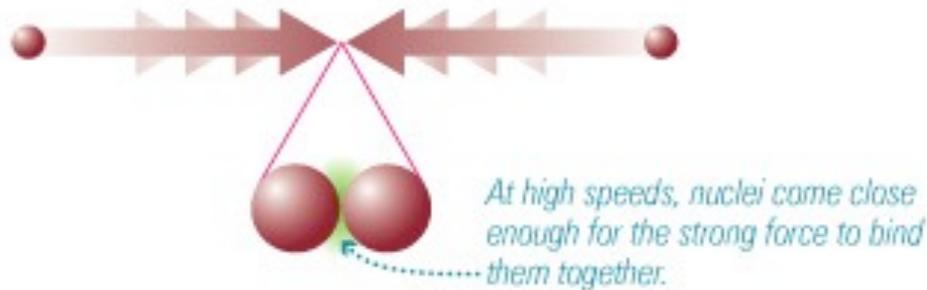
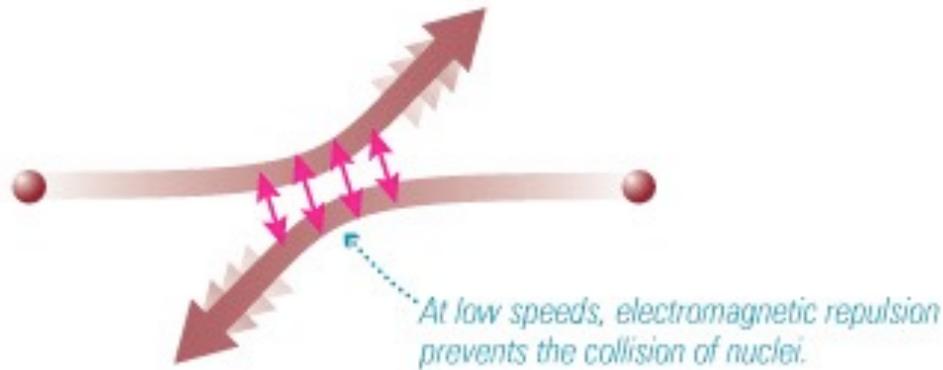


## ***Fusion***

- Small nuclei stick together to make a bigger one.
- (Example: the Sun, stars)

- High temperatures enable nuclear fusion to happen in the core.





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High temperatures enable nuclear fusion to happen in the core.

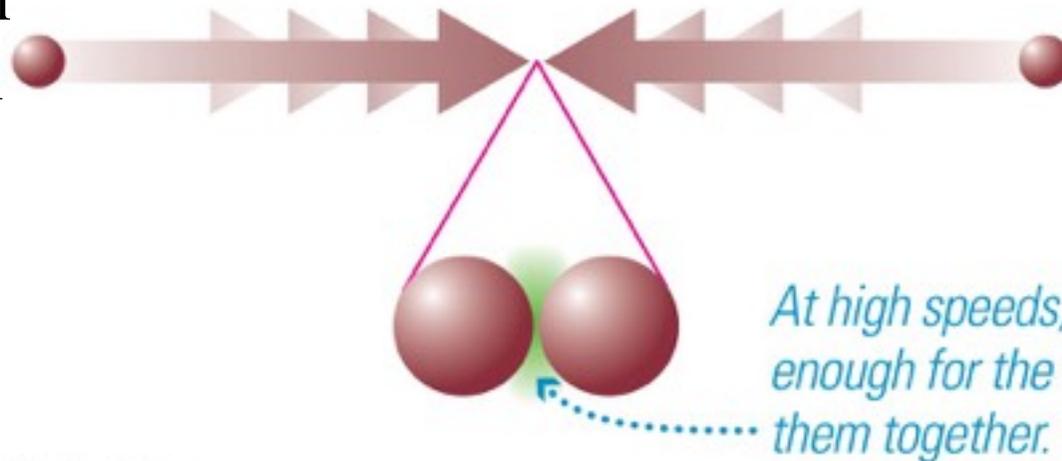
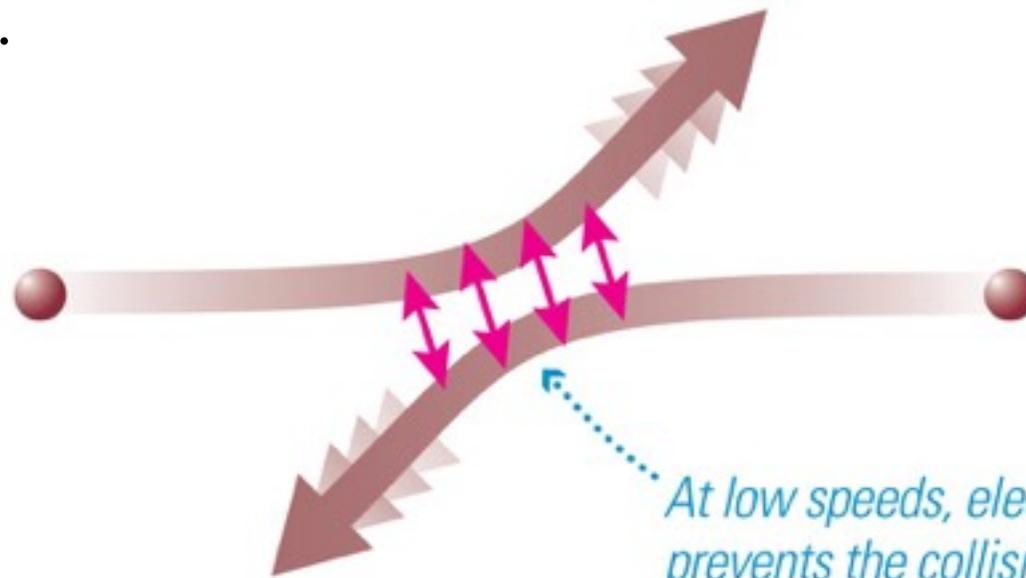
Positively charged protons repel each other.

Fusion only happens when the strong nuclear force is stronger than this repulsion, which only happens at very small separations. High temperatures are required to move fast enough to get that close.

High temperatures enable nuclear fusion to happen in the core.

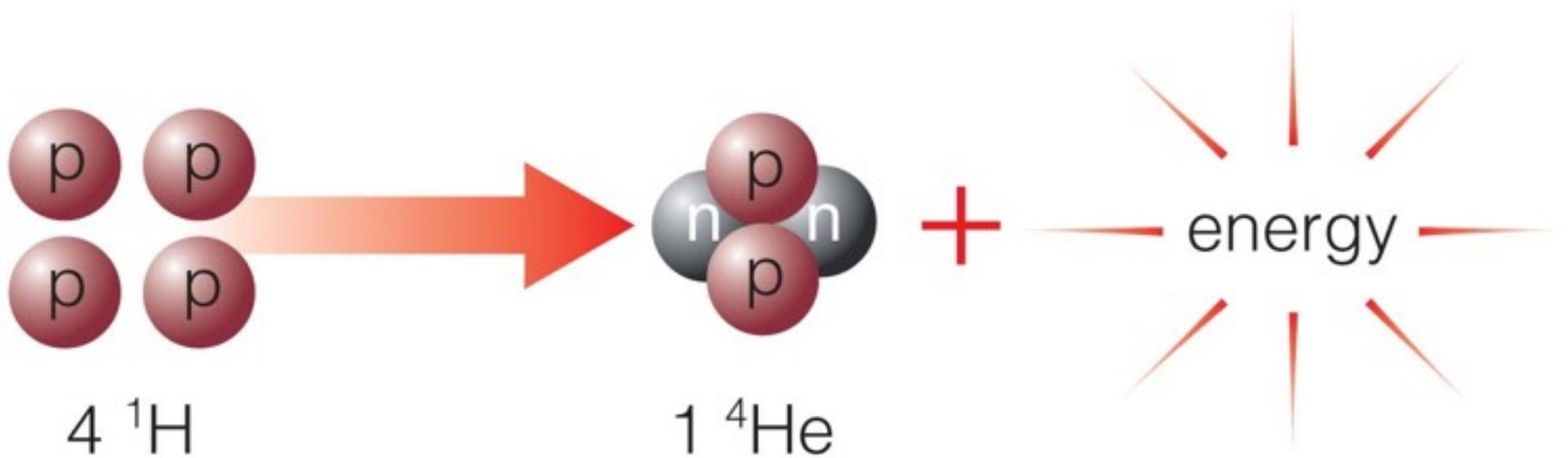
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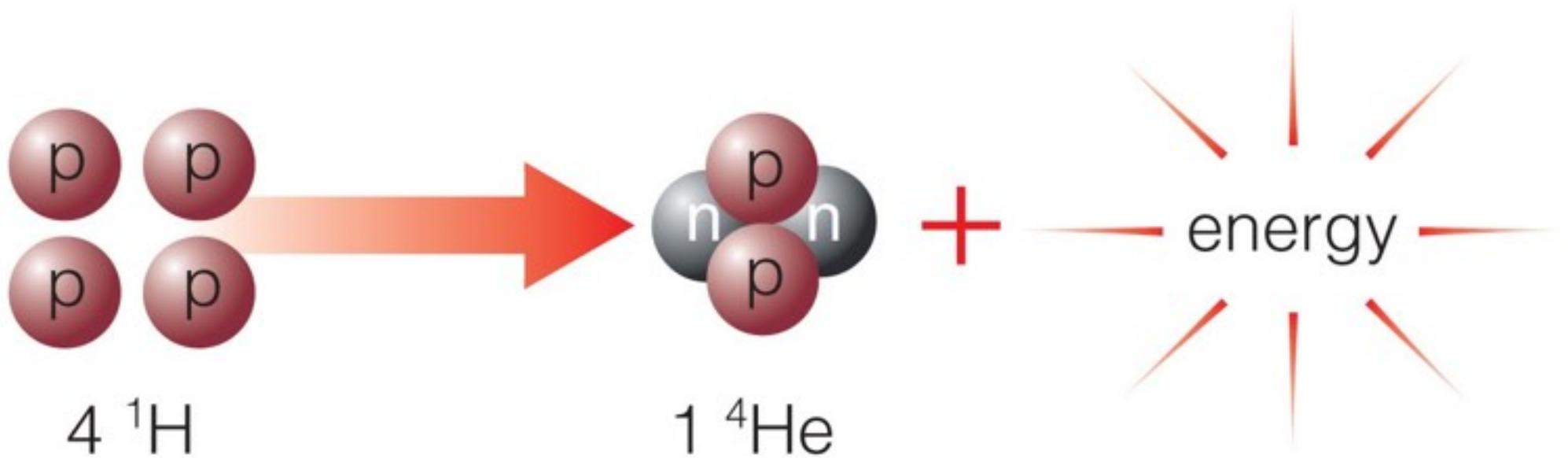


# Four fundamental forces

- Gravity
  - e.g, planetary orbits
  - falling objects
- Electromagnetism
  - attraction and repulsion of electric charges
  - magnets
- Strong nuclear force
  - fusion: binds protons together in atomic nuclei
- Weak nuclear force
  - fission; radioactive decay



- The Sun releases energy by fusing four hydrogen nuclei into one helium nucleus.
- Fusion is driven by the strong nuclear force after gravity heats a star's core enough to overcome the electrostatic repulsion of protons.



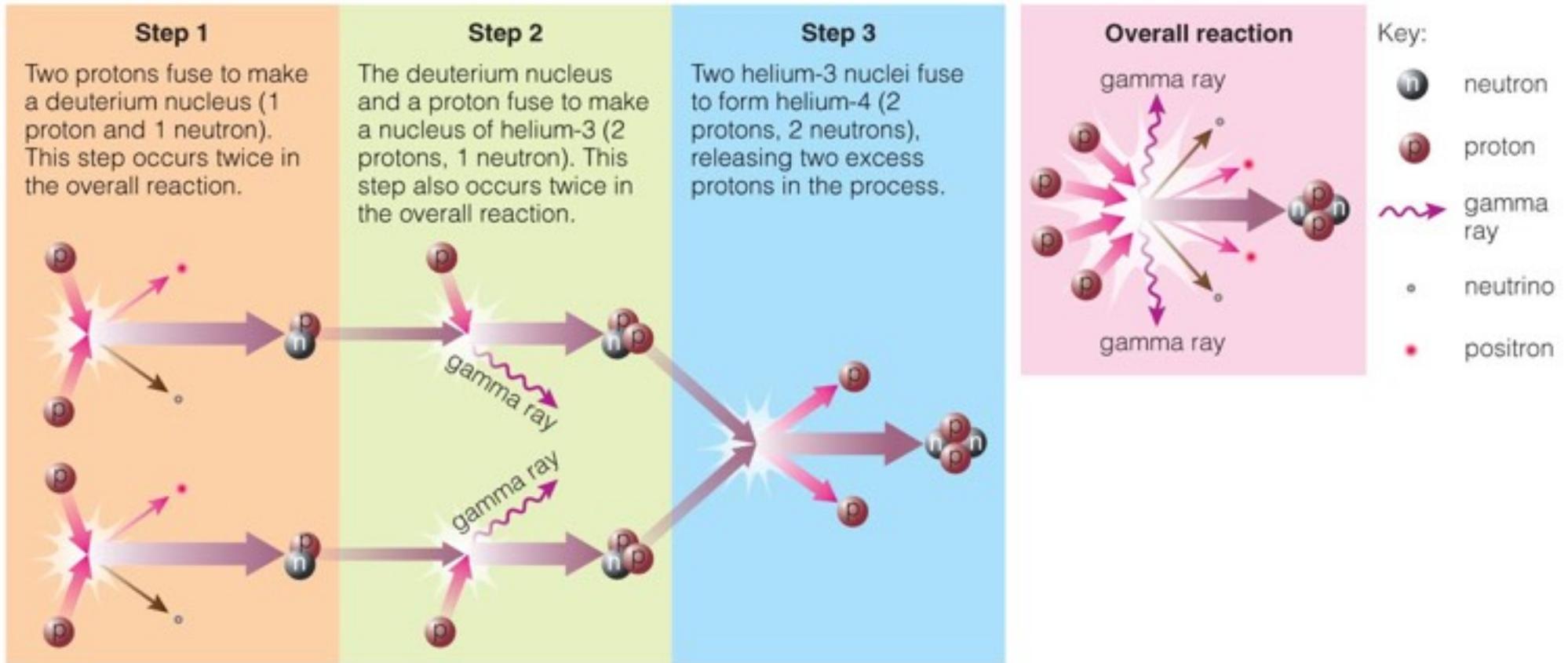
Sun releases energy by fusing four hydrogen nuclei into one helium nucleus.

Starting point is 4 protons.

End point is 2 p + 2 n (a helium nucleus) + energy

There are several steps required to make this happen.

## Hydrogen Fusion by the Proton-Proton Chain



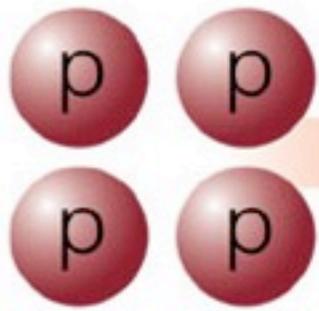
Interactive Figure 

- The **proton–proton chain** is how hydrogen fuses into helium in Sun.

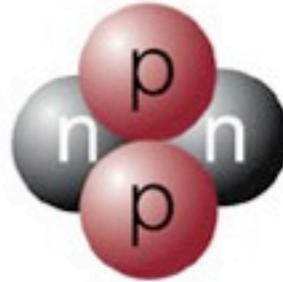
*Proton–proton chain* is how hydrogen fuses into helium in Sun

- step 1:  $p + p$  makes D (deuterium)
- step 2:  $D + D$  makes  ${}^3\text{He}$  (helium 3)
- step 3:  ${}^3\text{He} + {}^3\text{He}$  makes  ${}^4\text{He}$  (helium 4)
  - plus energy plus 2 spare protons and neutrinos.

The first step is the hardest -  
on average, takes 10,000,000 years to occur in the sun.

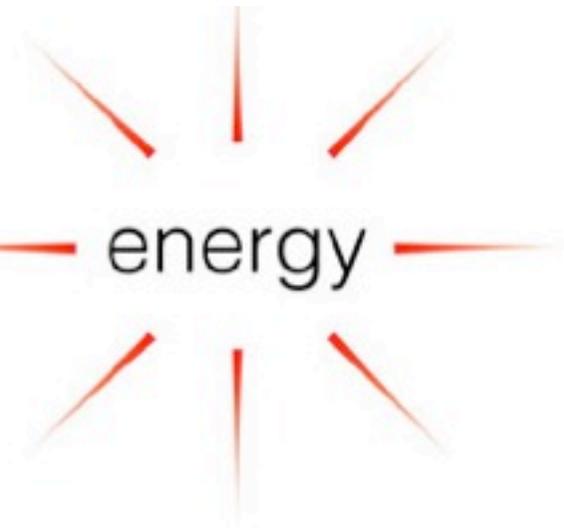


4  $^1\text{H}$



1  $^4\text{He}$

+



**Net Result:**

**IN**

4 protons

**OUT**

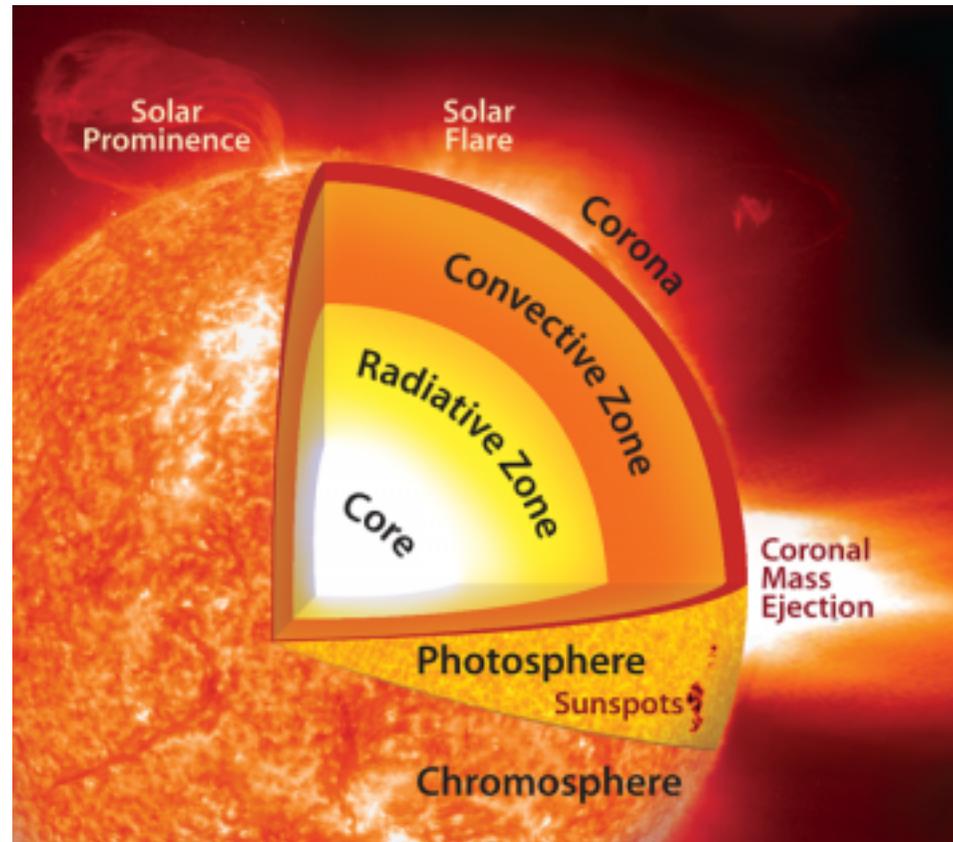
$^4\text{He}$  nucleus  
 2 gamma rays  
 2 positrons  
 2 neutrinos

$E = mc^2$  :

**Total mass is  
 0.7% lower.**

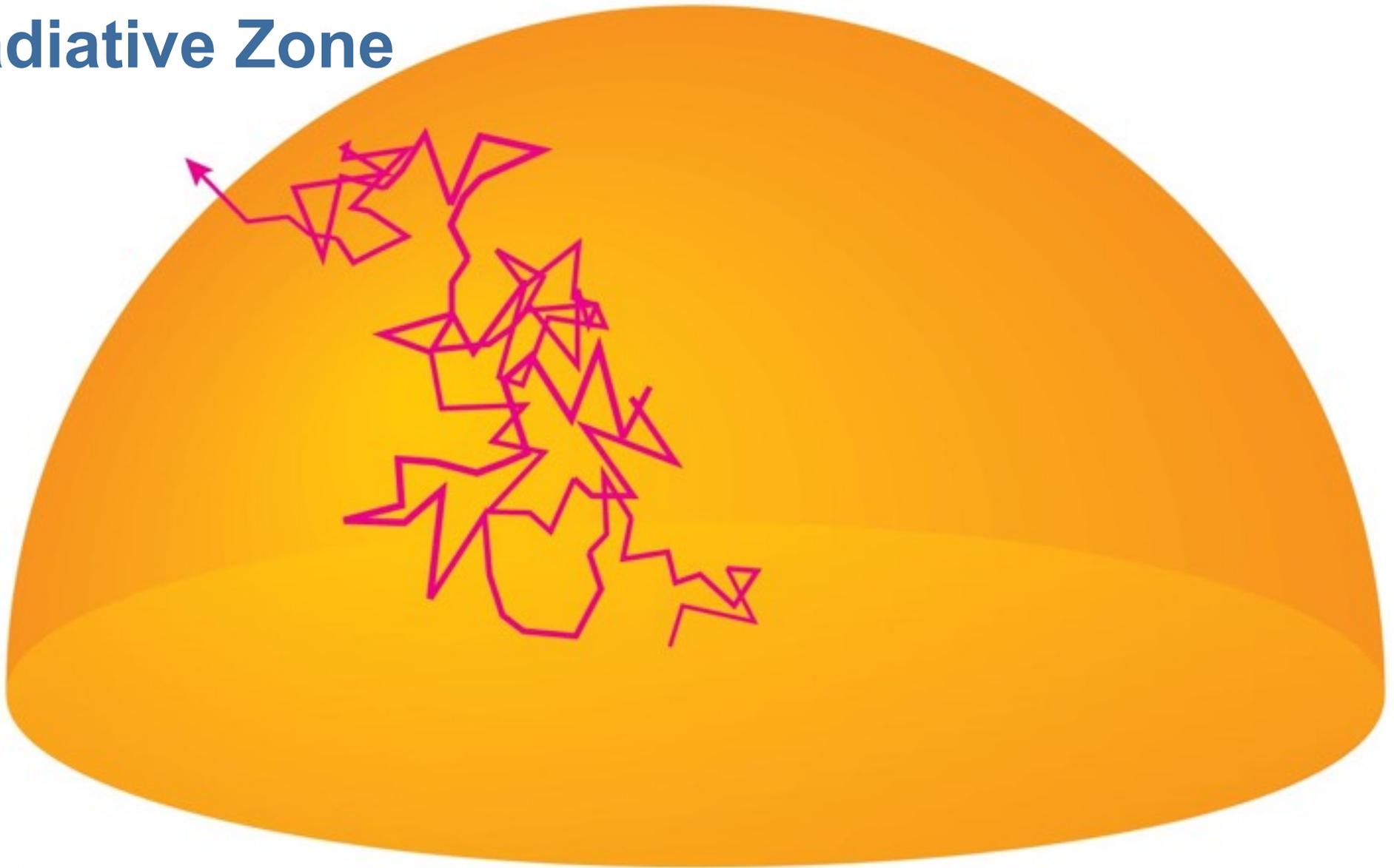
# Energy transport through the Sun

- Energy is produced in the core
- Transported through
  - Radiative Zone by photons
  - Convective Zone by gas motions
  - Nature chooses whichever is more efficient



# Energy transport through the Sun

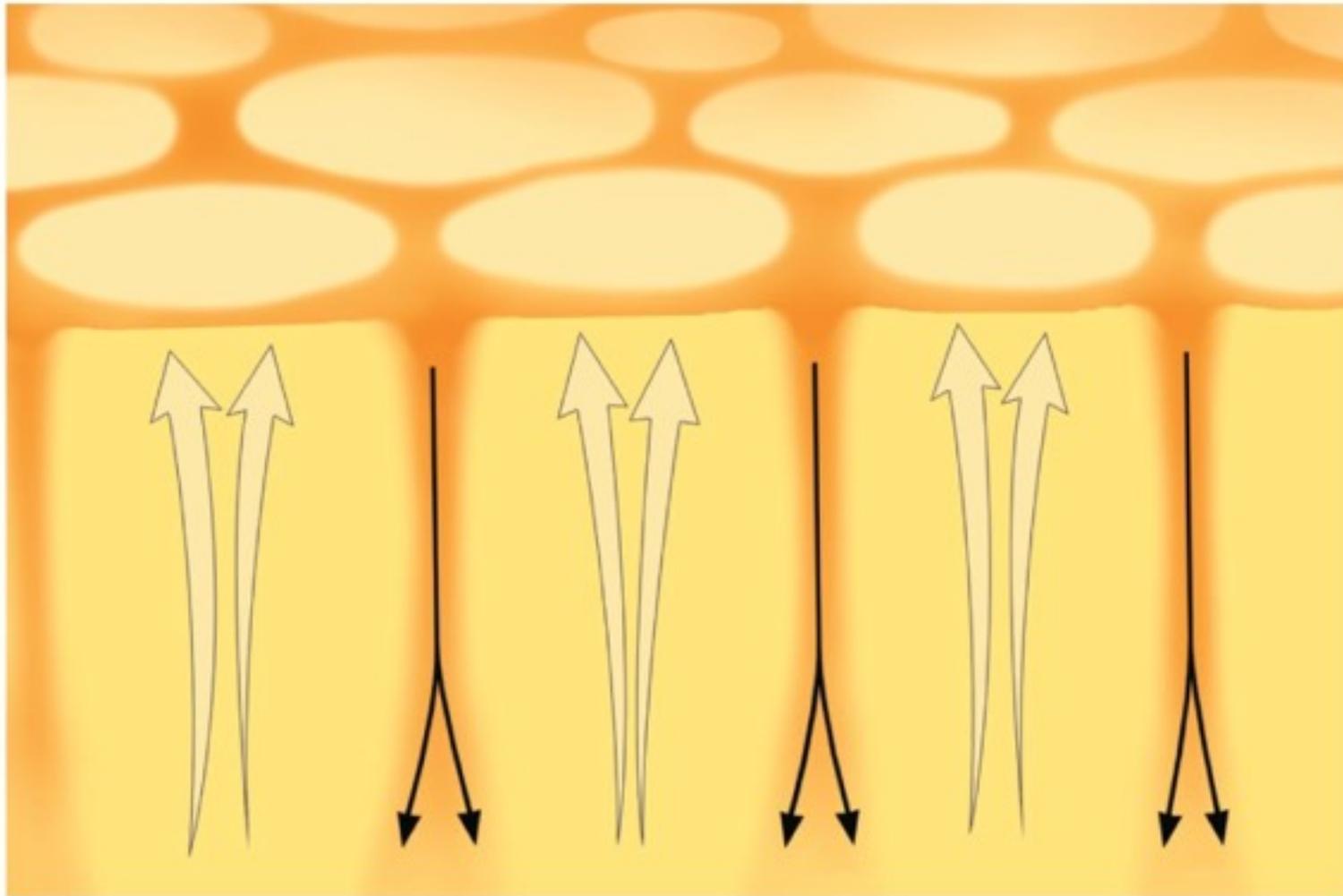
## Radiative Zone



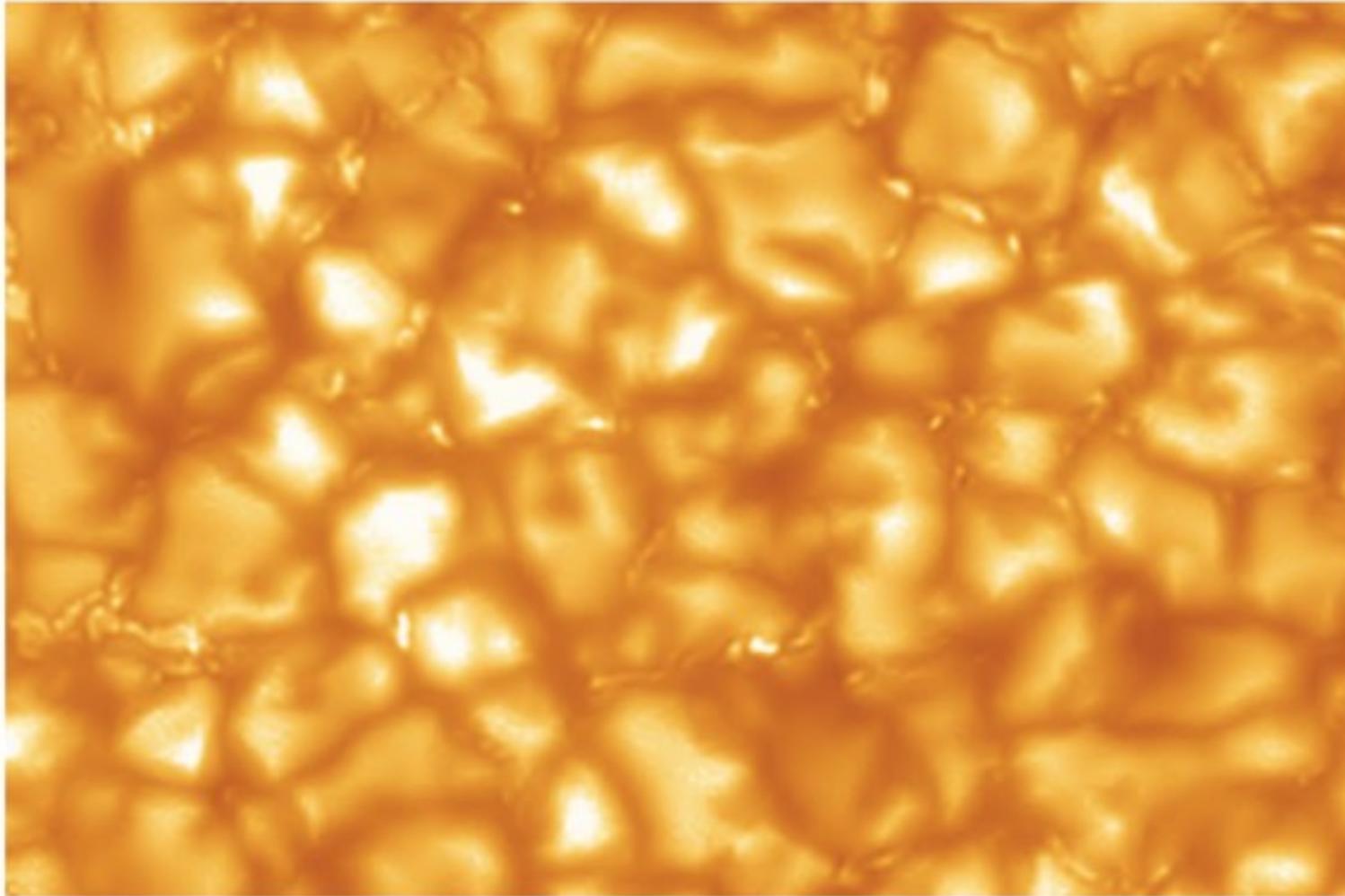
- Energy gradually leaks out of radiation zone in form of randomly bouncing photons.

# Energy transport through the Sun

## Convective Zone



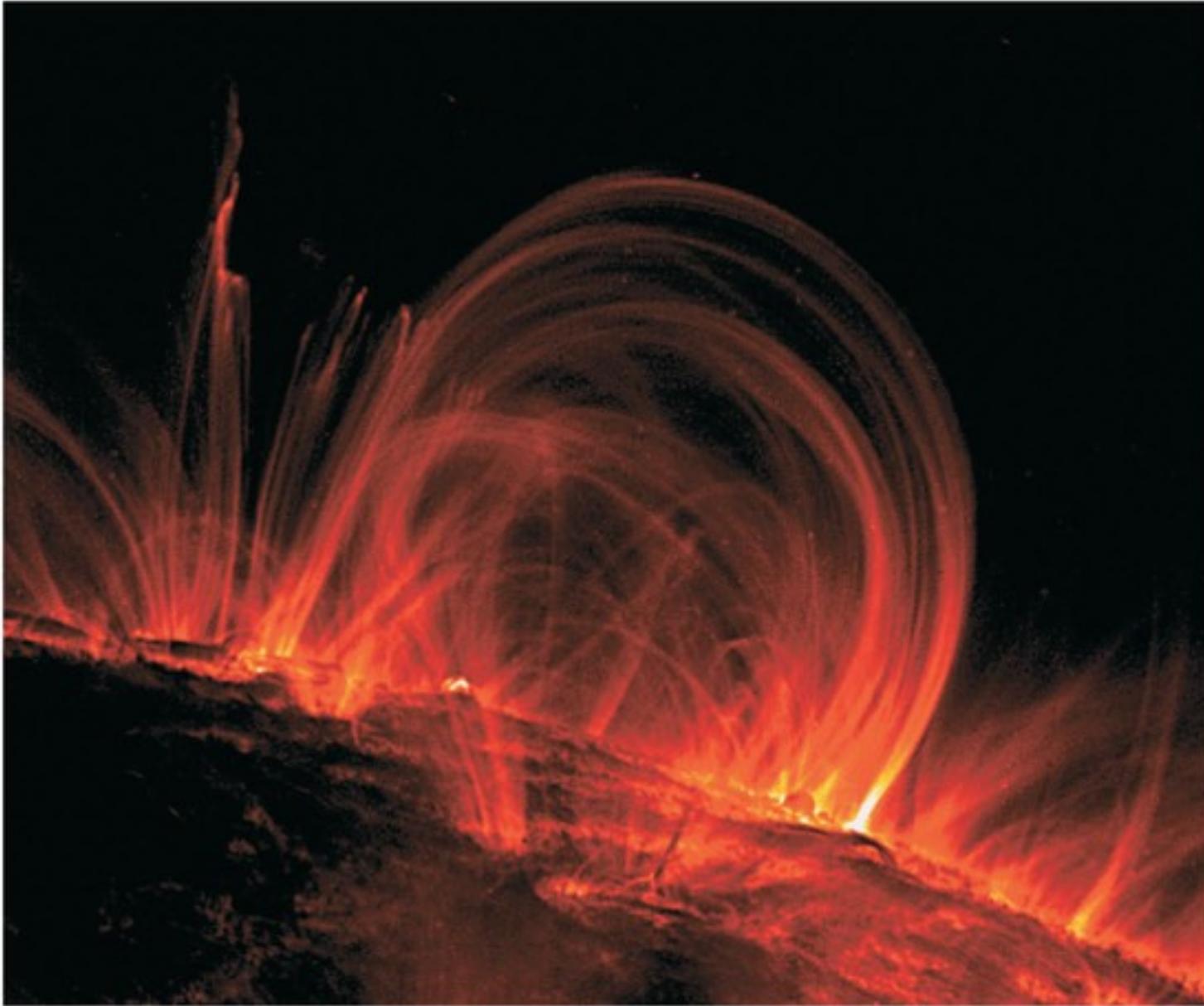
a This diagram shows convection beneath the Sun's surface. Hot gas (light yellow arrows) rises while cooler gas (black arrows) descends around it.



**b** This photograph shows the mottled appearance of the Sun's photosphere. The bright spots, each about 1000 kilometers across, correspond to the rising plumes of hot gas in part a.

- Bright blobs on photosphere show where hot gas is reaching the surface.

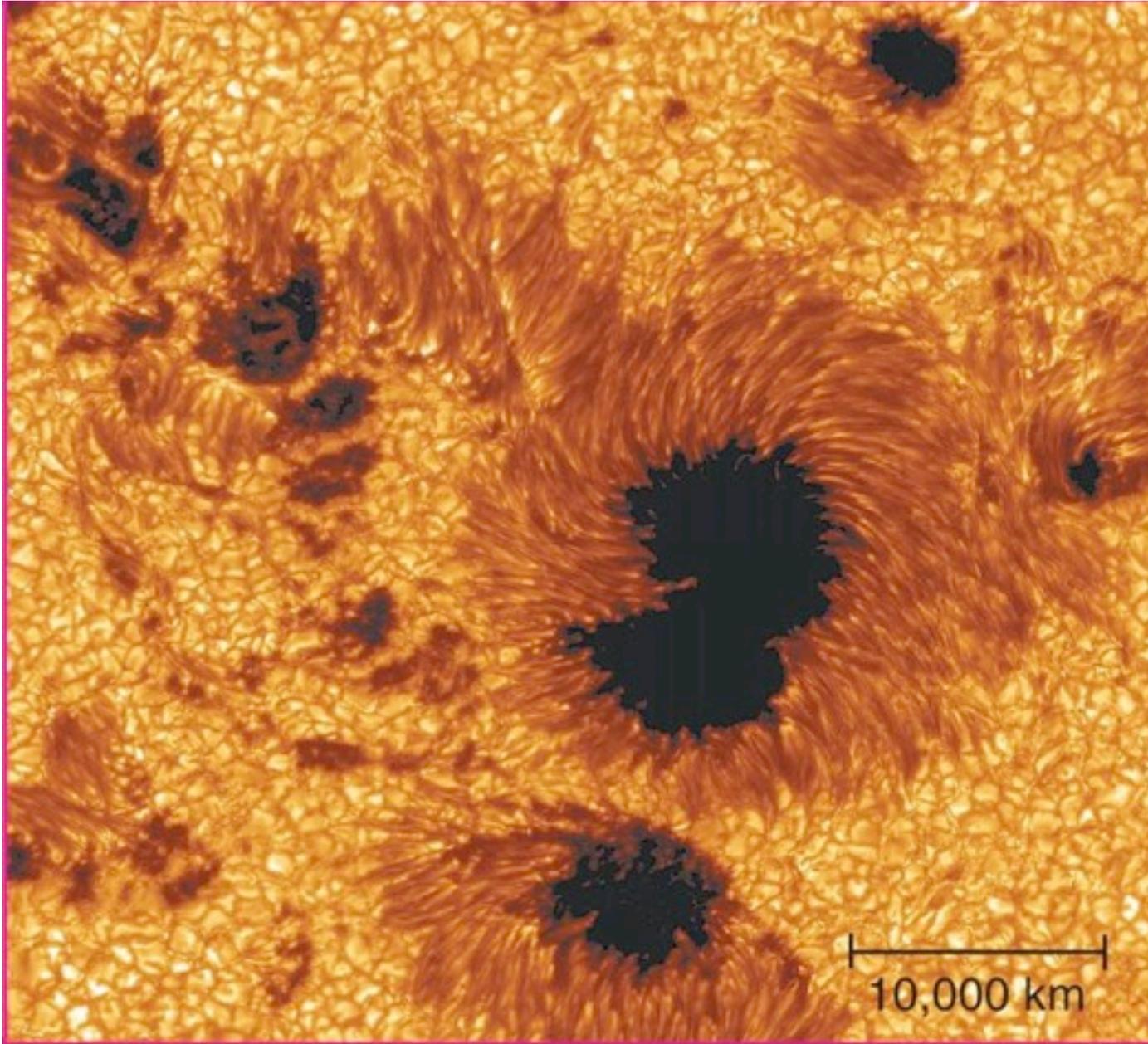
# Solar activity



**b** This X-ray photo (from NASA's *TRACE* mission) shows hot gas trapped within looped magnetic field lines.

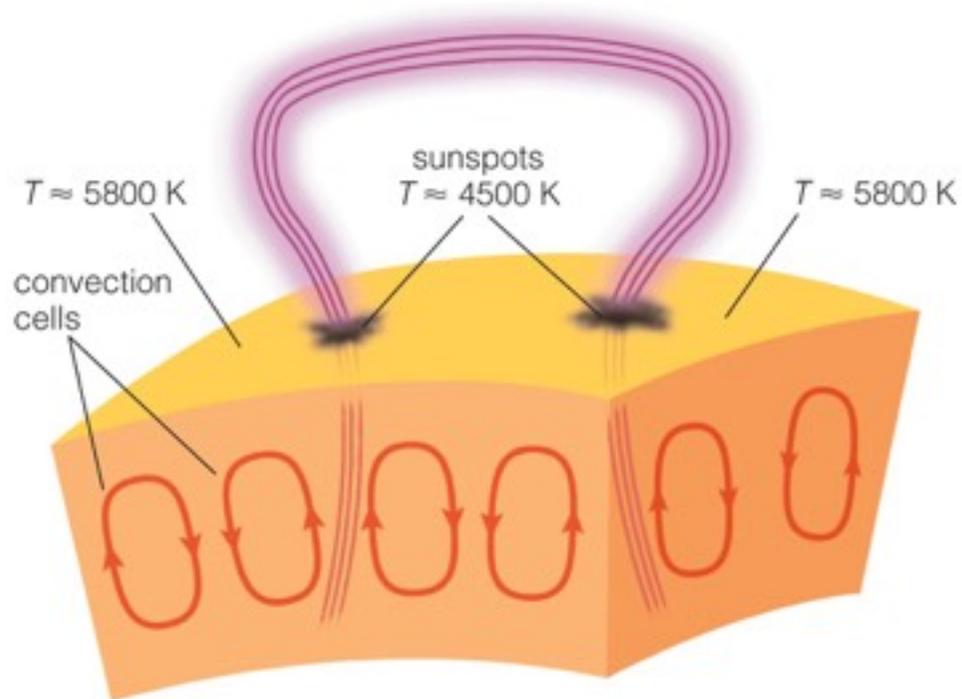
# Solar activity is like "weather".

- Sunspots
- Solar flares
- Solar prominences
  
- All these phenomena are related to magnetic fields.

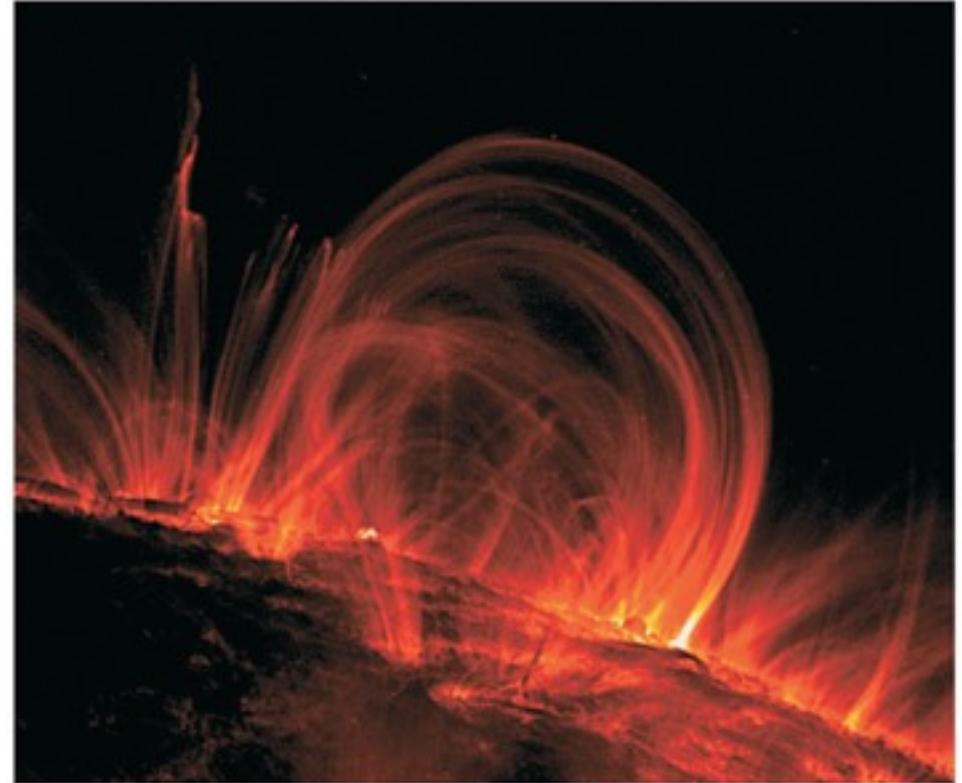


## ***Sunspots***

- Are cooler than other parts of the Sun's surface (4000 K)
- Are regions with strong magnetic fields



a Pairs of sunspots are connected by tightly wound magnetic field lines.

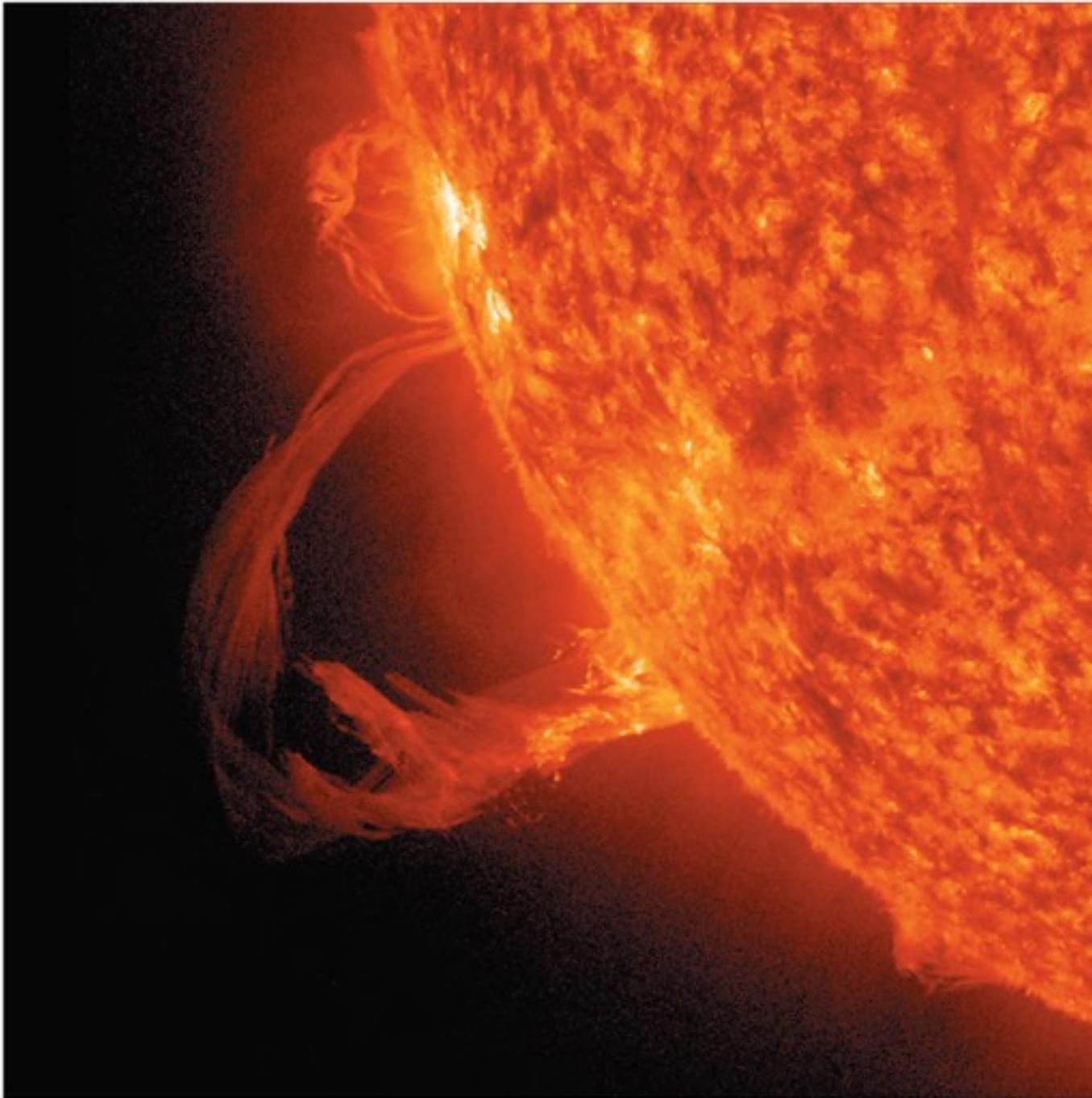


b This X-ray photo (from NASA's *TRACE* mission) shows hot gas trapped within looped magnetic field lines.

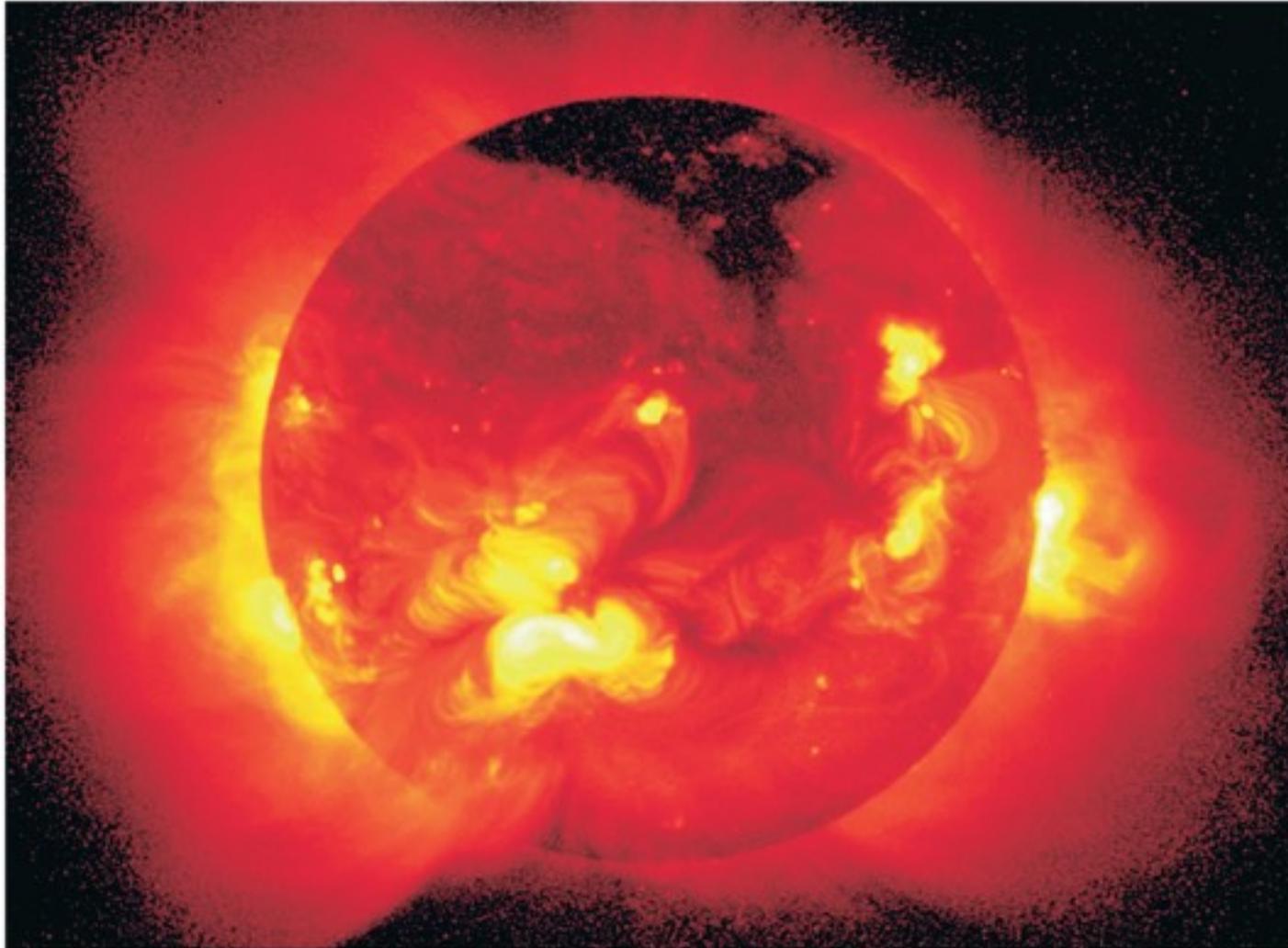
- Loops of bright gas often connect sunspot pairs.



- Magnetic activity causes ***solar flares*** that send bursts of X rays and charged particles into space.

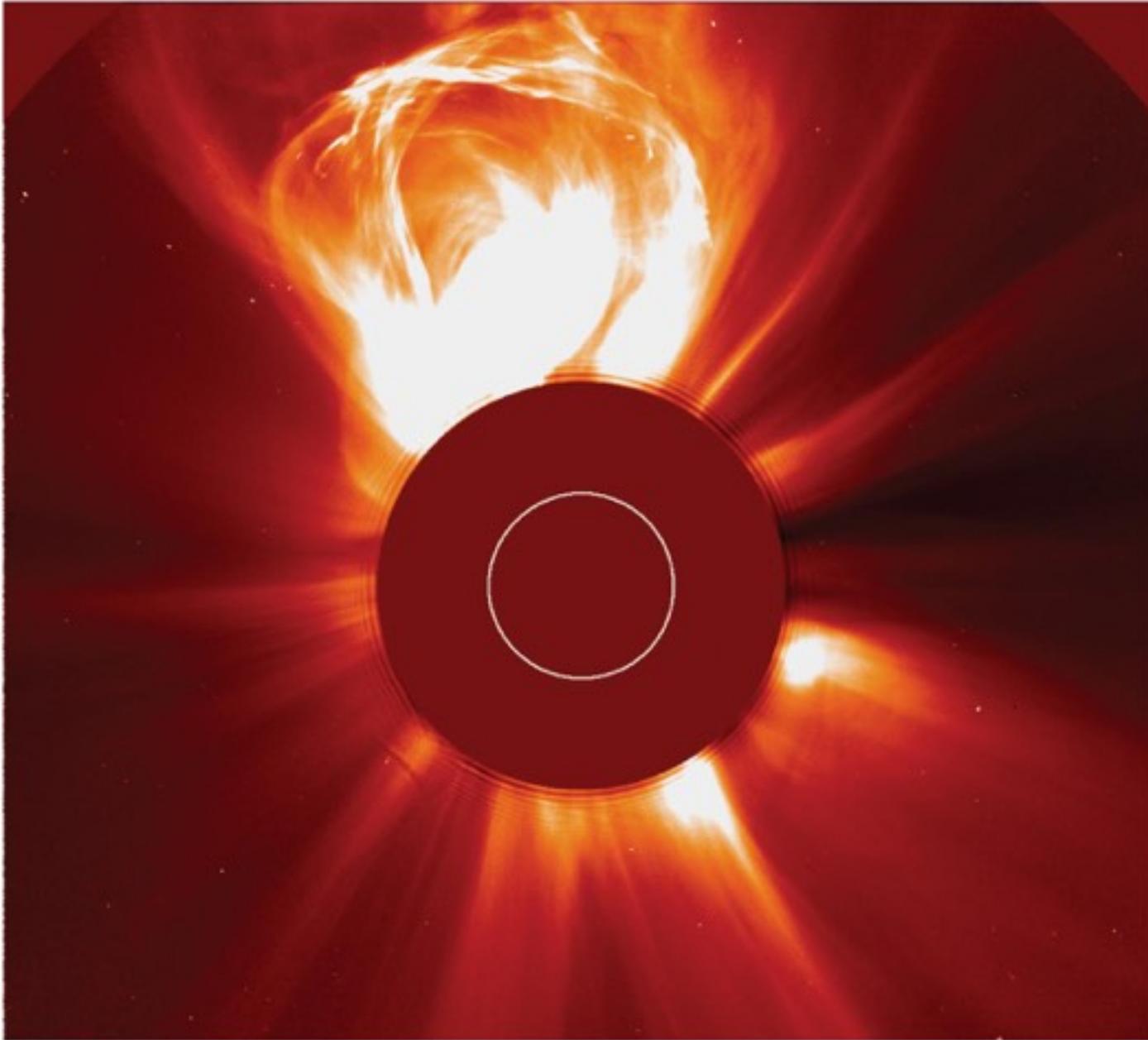


- Magnetic activity also causes ***solar prominences*** that erupt high above the Sun's surface.

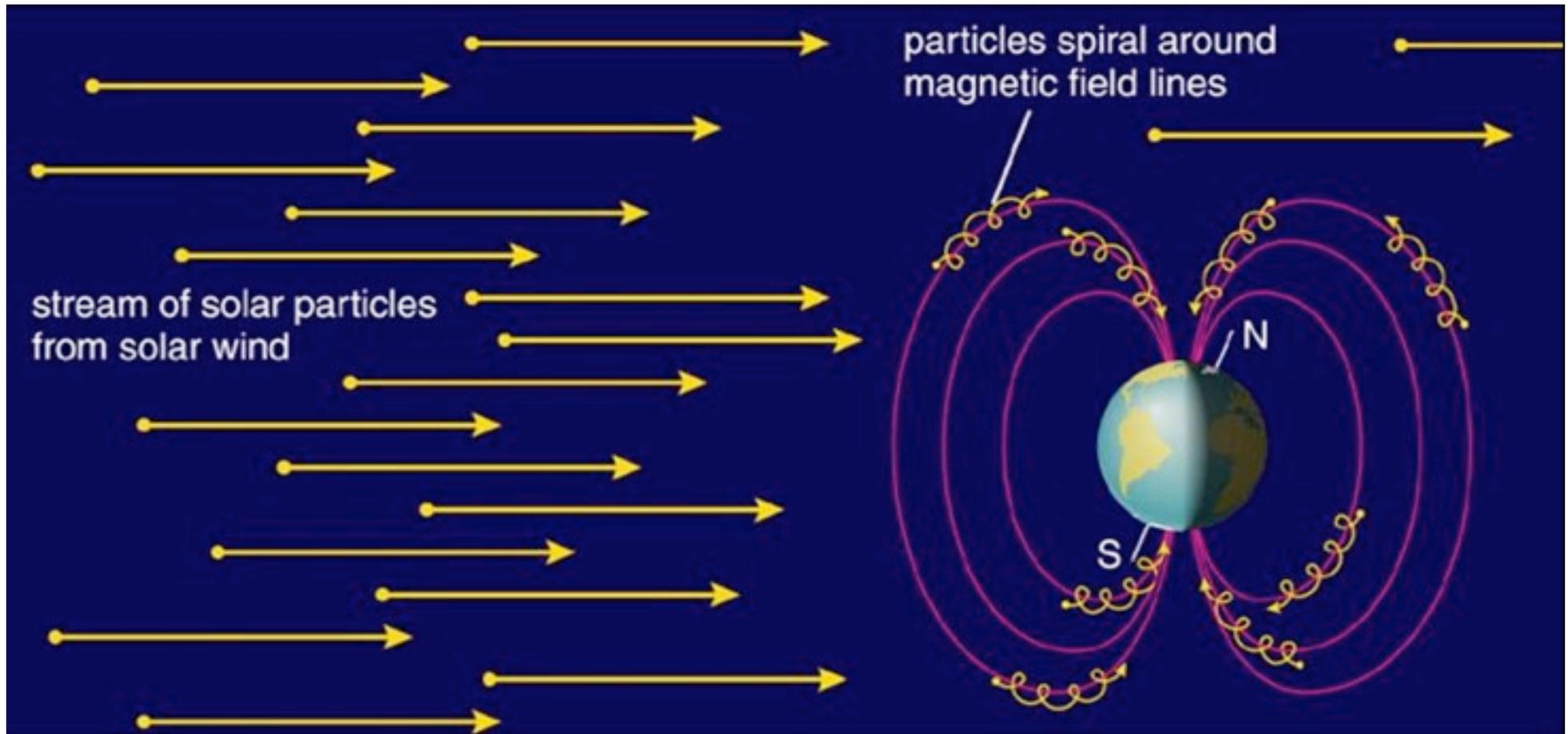


Interactive Figure 

- The corona appears bright in X-ray photos in places where magnetic fields trap hot gas.



- ***Coronal mass ejections*** send bursts of energetic charged particles out through the solar system.



- Charged particles streaming from the Sun cause aurora near poles
- Can sometimes disrupt electrical power grids and can disable communications satellites.